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CONDUCTED
WITH THE CO-OPERATION OF THE
AMERICAN PHYSICAL SOCIETY
BY
EDWARD L. NICHOLS,
ERNEST MERRITT, and FREDERICK BEDELL

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JUNE, 1912

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THE

PHYSICAL REVIEW.

CONVECTION AND CONDUCTION OF HEAT IN GASES.

By Irving Langmuir.

Part I. Historical.

THE loss of heat by convection from a heated body has apparently always been looked upon as a phenomenon essentially so complicated that a true knowledge of its laws seemed nearly impossible. A. Oberbeck[1] gives the general differential equations for this problem but finds it impossible to solve them for actual cases. L. Lorenz[2] for the case of vertically placed plane surfaces is able to obtain some approximate solutions which agreed fairly well with some of the older experimental work. But as an illustration of the view taken even recently by one familiar with practically all the literature I might quote from a paper by A. Russell:[3] "The phenomenon of the convection of heat at the surface of a body immersed in a cooling fluid is one which does not lend itself readily to mathematical calculation. If the fluid be a gas the variations of the pressure, density, and velocity at different points of the gas so complicate the problem that little progress towards a complete solution has yet been made."

In his own paper Russell then feels compelled to make the following simplifying assumptions in dealing with this problem. "The liquid is supposed to be opaque to heat rays. It is also supposed to have *no viscosity* (italics mine). The liquid therefore slips past the surface of the solid. In addition it is supposed to be incompressible. Hence we should only expect the solutions to give roughly approximate values when applied to the problems of spheres and cylinders being cooled by currents of air."

[1] Ann. Phys., *7*, 271 (1879).
[2] Ann. Phys., *13*, 582 (1881).
[3] Phil. Mag., *20*, 591 (1910).

Kennelly[1] who made very elaborate measurements of the "Convection of Heat from Small Copper Wires" also finds the theory involved very complicated and is satisfied to derive empirical laws to express his results. He says "The lateral conduction through the air is negligible because the air does not remain at rest but expands and flows convectively. Consequently we may safely ignore conductive thermal loss." "Convection loss from the wire is a hydrodynamic phenomenon, involving the flow of air past the surface of the wire, and the amount of heat which this moving stream can carry off. Very little seems to be known quantitatively about convection."

Such views as these are not conducive to the finding of simple laws if such exist.

The writer has long felt that the assumption that the effect of the viscosity of the gas is negligible is unwarranted. In the case of convection from small wires it has seemed rather that it is one of the most essential of the factors involved. The writer's views on this were given in his thesis on some reactions around glowing Nernst filaments,[2] from which the following extracts are taken.

"In the case of electrically heated glowing filaments the rate of loss of energy is equal to the watts input. If, as is often the case, the radiation loss may be calculated, this may be subtracted and one thus obtains the energy lost by convection and heat conduction through the gas. Now according to the kinetic theory the viscosity of a gas increases with the square root of the absolute temperature; the driving force of the convection being proportional to the difference of density between the hot and cold gas, increases only very slowly with increasing temperature. Therefore in the immediate neighborhood of the filament the flow of gas is small and the heat must be carried away practically only by conduction."

"It would seem, however, as though heat conduction alone would come into account up to a distance of about 0.2 mm. from the center of the wire. It is highly probable that at very high temperatures, for example 2200°, the motion of the gas in the immediate neighborhood of the wire would not perceptibly increase but probably decrease, while at the same time the heat conductivity of the gas would increase very greatly. (For example the heat conductivity, **k**, at 2300° K. is 27×10^{-5} while at 273° K. it is only 4.7×10^{-5}.) Thus even at a distance from the wire where the motion of the gas is considerable, the conduction will be more important than the convection."

[1] Trans. Amer. Inst. E. E., *28*, 363 (1909).

[2] Über partielle Wiedervereinigung dissocierten Gase im Verlauf einer Abkuhlung. Inaugural Dissertation, Göttingen, 1906.

"Therefore up to a distance of a few tenths of a millimeter from the glowing body one may consider the heat to be carried only by radiation and *conduction*."

"If **W** is the rate of energy loss per cm. of length of the wire and **k** the coefficient of heat conductivity, a the radius of the wire and T_0 its temp., then for the temp. T at a distance r from the axis of the wire the relation holds:"

$$(1) \qquad T_0 - T = \frac{\mathbf{W}}{2\pi\mathbf{k}} ln \frac{r}{a}.$$

Some later experiments by the author in this research laboratory[1] led to some very interesting results as to the heat losses in hydrogen from tungsten wires at very high temperatures. In connection with this work it was highly desirable to know the laws of heat "convection" more definitely, so the work described in the present paper was undertaken to test out the theory advanced in the above mentioned dissertation and, if the results should warrant it, to develop the theory further and give it more definite form. Several considerations had made it seem probable that the above theory would be fairly close to the truth. For example it had been noticed that the watts loss from a wire was very nearly independent of the position of the wire, that is, whether it were placed vertically or horizontally. Now the lines of flow of the heated air around the wire would be totally dissimilar in these two cases. Yet it was found that the energy necessary to maintain a piece of pure platinum wire at any given temperature (resistance kept constant) never differed by more than 6–8 per cent. for the vertical and the horizontal wire and at a bright red heat or above the difference became negligibly small. This was strong indication that the heat loss was dependent practically only on heat conduction very close to the filament and that the convection currents had practically no effect except to carry the heat away after it passed out through the film of adhering gas.

The thickness of the film of gas through which the conduction takes place can be calculated from equation (1) if the temp. of the wire, its diameter and the heat conductivity are known. This last quantity however varies considerably with the temp. and there is little data available on the heat conductivities of gases at very high temperatures.

Part II. Theoretical. Heat Conductivity of Gases at High Temperatures.

The literature on the heat conductivity of gases is relatively meager compared with the wealth of material on the viscosity of gas. For-

[1] Trans. Amer. Electrochem. Soc., *20*, p. 335 (1911).

tunately the kinetic theory furnishes us a means of calculating the heat conductivities from the viscosities.

Meyer[1] gives the relation:

$$\mathbf{k} = 1.603\mathbf{h}\mathbf{c}_v,$$

$\mathbf{k}$ = heat conductivity, $\mathbf{h}$ = viscosity, $\mathbf{c}_v$ = specific heat (per gram) at constant volume.

Eucken in a recent paper[2] shows that the constant (which will be denoted by K) for the monatomic gases, helium and argon, is 2.50 instead of 1.603 and that for diatomic gases, H_2, O_2, N_2, and air it is 1.90. He also shows that K is independent of the temperature over a wide range.

In view of the serious difficulties involved in measurements of heat conductivities of gases and the ease and accuracy with which the viscosities can be measured it seems highly probable that the heat conductivities calculated in this way are much more reliable than those measured directly.

Viscosity of Gases.

The variation of the viscosity of gases with the temperature has been the subject of many careful researches in the last few years. In every case Sutherland's formula seems to agree within the experimental error with the results, at least in all cases of gases above their critical temperatures.

Sutherland's formula may be written

$$\mathbf{h} = \frac{KT^{\frac{1}{2}}}{1 + \frac{C}{T}}. \tag{2}$$

The values of K and C for H_2, air and Hg are:

Gas.	$10^6 K$	C	Observer.
H_2.....	6.6	77	Fisher, PHYS. REV., 24, 385 (1907).
Air.....	15.0	124	Fisher, PHYS. REV., 29, 106 (1909).
Hg.....	65.0	960	See below.

The viscosity of mercury vapor has been determined by Koch[3] and his results were confirmed by Noyes and Goodwin.[4] These results do not agree with Sutherland's formula, probably partly because of errors made at low temperatures and partly because the temperature of observation was much below the critical temp. of mercury. Koch gives for the

[1] Kinetic Theory of Gases.

[2] Physik. Zeitschr., *12*, 1101 (1911).

[3] Ann. Phys., *19*, 857 (1883).

[4] PHYS. REV., *4*, 207 (1896).

highest temperature at which he made measurements:

$$\text{at } 380^\circ \text{ C. } 10^3\mathbf{h} = 0.654,$$

or extrapolating from his results:

$$\text{at } 420^\circ \text{ C. } 10^3\mathbf{h} = 0.718.$$

This last result is probably far enough above the boiling point so that the viscosity is nearly normal and for temperatures above this, Sutherland's formula would probably give the correct values. A. O. Rankine[1] shows that

$$C = \frac{T_c}{1.15},$$

where T_c is the critical temp. As no data are available for the critical temp. of mercury it may be roughly calculated. The ratio of the boiling points (in ° K.) and critical temps. for most liquids is nearly constant, about 1 : 1.7. Thus the critical temp. of mercury would be about 1100° K. Hence $C = 1/1.15 \times 1100^\circ = 960$. From this and the viscosity, the value of K may be easily calculated. $K = 65.0 \times 10^{-6}$. This should be considered only a rough approximation.

Specific Heats.—The most reliable data seem to be those of M. Pier[2] who gives for the actual molecular specific heat (constant volume) at the temp. T (absolute):

$$\begin{aligned} \text{For } H_2 \quad & \mathbf{c_v} = 4.454 + .0009T, \\ \text{air} \quad & \mathbf{c_v} = 4.654 + .0009T, \\ \text{Hg} \quad & \mathbf{c_v} = 2.98. \end{aligned}$$

For the calculation of the heat conductivity we need the specific heats per gram. Assuming the "molecular weight" of air to be 28.8 we get

$$\begin{aligned} \text{For } H_2 \quad & \mathbf{c_v} = 2.21(1 + .0002T), \\ \text{air} \quad & \mathbf{c_v} = 0.1614(1 + .0002T), \\ \text{Hg} \quad & \mathbf{c_v} = 0.0149. \end{aligned}$$

Heat Conductivities.—For hydrogen and air $\mathbf{k} = 1.90\mathbf{hc_v}$.

For mercury vapor at high temperatures we may safely assume $\mathbf{k} = 2.5\mathbf{hc_v}$ although Schleiermacher[3] found experimentally a value of 3.15 for the constant at a temp. of 203° C.

[1] Proc. Roy. Soc. London, *A 84*, 181–92 (1910).

[2] Z. f. Electrochem., *15*, 536 (1909), and *16*, 899 (1910).

[3] Ann. phys., *36*, 346 (1889).

We thus obtain from the data for $\mathbf{h}$ and $\mathbf{c_v}$

$$\text{For } H_2 \quad \mathbf{k} = 28 \times 10^{-6}\sqrt{T}\cdot\frac{1 + .0002T}{1 + \frac{77}{T}}, \tag{3}$$

$$\text{air} \quad \mathbf{k} = 4.6 \times 10^{-6}\sqrt{T}\cdot\frac{1 + .0002T}{1 + \frac{124}{T}}, \tag{4}$$

$$\text{Hg} \quad \mathbf{k} = 2.4 \times 10^{-6}\sqrt{T}\cdot\frac{1}{1 + \frac{960}{T}}. \tag{5}$$

These equations should hold especially well at very high temperatures, when the gases are far above their critical temperatures.

But in the problem of the convection of heat from a hot wire, the difference in temperature between the wire and the atmosphere around it is often so great that we cannot consider the heat conductivity as being constant. We shall need to take into account the variation of the heat conductivity in the different layers of hot gas around the wire.

In any problem in heat conduction where steady conditions prevail we may write:

$$\frac{dq}{ds} = \mathbf{k}\frac{dT}{dx}, \tag{6}$$

where dq = heat flowing per second through the area ds, $\mathbf{k}$ = heat conductivity, T = temperature, x = distance measured perpendicular to the surface ds.

If the heat flux is uniformly distributed over the whole surface s then we may separate the variables and integrate the equation as follows:

$$\int \mathbf{k}dT = q\int\frac{dx}{s}, \tag{7}$$

where $\mathbf{k}$ is a function of T only, and s is a function of x only.

If we measure the rate of loss of heat in watts (W) we have:

$$W = \frac{4.19\int \mathbf{k}dT}{\int\frac{dx}{s}}. \tag{8}$$

Cylindrical Wires.—Let us consider a wire of diameter a surrounded by a cylindrical film of gas of a diameter b. Let T_2 be the temperature of the wire and T_1 the temperature of the gas at the outer surface of the

film, *i. e.*, at a distance $\frac{1}{2}b$ from the center of the wire. Then, if l is the length of the wire,

$$\int \frac{dx}{s} = \frac{1}{2\pi l} ln \frac{b}{a}. \tag{9}$$

If **W** be the watts of heat energy conducted away from the wire *per unit* of length then

$$\mathbf{W} = \frac{4.19 \times 2\pi}{ln \frac{b}{a}} \int_{T_1}^{T_2} \mathbf{k} dT. \tag{10}$$

For convenience place

$$\varphi = 4.19 \int_0^T \mathbf{k} dT, \tag{11}$$

and place

$$\mathbf{s} = \frac{2\pi}{ln \frac{b}{a}}. \tag{11a}$$

Whence

$$\mathbf{W} = \mathbf{s}(\varphi_2 - \varphi_1). \tag{12}$$

Plane Surface.—Consider a plane surface of area s with an adhering film of gas of the thickness B. Equation (8) then becomes

$$W = 4.19 \frac{s}{B} \int_{T_1}^{T_2} \mathbf{k} dT = \frac{s}{B} (\varphi_2 - \varphi_1). \tag{13}$$

The function φ can be readily calculated and plotted as a function of T. For any gas the heat conductivity **k** can be put in the form

$$\mathbf{k} = A(1 + \alpha T) \frac{T^{\frac{1}{2}}}{1 + \frac{C}{T}}; \tag{14}$$

as a very close approximation we have

$$\varphi = 4.19A(1 + 0.6\alpha T) \int_0^T \frac{T^{\frac{1}{2}} dT}{1 + \frac{C}{T}}, \tag{15}$$

and (accurately)

$$\int_0^T \frac{T^{\frac{1}{2}} dT}{1 + \frac{C}{T}} = \tfrac{2}{3} T^{\frac{3}{2}} - 2CT^{\frac{1}{2}} + 2C^{\frac{3}{2}} \tan^{-1} \sqrt{\frac{T}{C}}. \tag{16}$$

The values of φ for air, hydrogen and mercury vapor from 0° K. up

to high tempreatures have been calculated (by slide rule) and are given in the following table:

TABLE I.

Table of φ, in Watts per Cm., as Function of Absolute Temp. (° K.).

T°K.	Hydrogen.	Air.	Mercury Vapor.
0°	0.0000	0.0000	
100°	.0329	.0041	
200°	.1294	.0168	
300°	.278	.0387	
400°	.470	.0669	
500°	.700	.1017	0.0165
700°	1.261	.189	.0356
900°	1.961	.297	.0621
1100°	2.787	.426	.0941
1300°	3.726	.576	.1333
1500°	4.787	.744	.1783
1700°	5.945	.931	.228
1900°	7.255	1.138	.284
2100°	8.655	1.363	.345
2300°	10.18	1.608	.411
2500°	11.82	1.871	.481
2700°	13.56		.556
2900°	15.54		.636
3100°	17.42		.719
3300°	19.50		.807
3500°	21.79		.898

Theory of Conducting Film.

Let us assume that the viscosity of the gas causes the heat to flow from a hot wire as though there were around the wire a stationary cylindrical film of gas (of diameter b) through which heat is carried only by conduction.

If we know the watts lost by a wire per cm. of length we are now in a position to calculate the diameter b of this film.

It is to be expected that b will vary with the diameter of the wire. Mr. E. Q. Adams of this laboratory has derived a relation between b and the diameter of the wire, a, which has been well verified by the experimental results. Mr. Adams' derivation is:

Derivation of $b \ln \frac{b}{a} = 2B$.

"The effective thickness of the film of air near a plate or wire is the distance the heat must travel before the heat flux due to temperature difference becomes negligible compared with that due to convection.

"At constant pressure the temperature and the temperature gradient at the outside surface of the film are assumed to be independent of the diameter of the wire.

"Consider now the analogy between the cases of heat conduction from a wire and from a plane under similar conditions of temperature, etc.

"Let r = the distance of any isotherm from the axis of the wire.

"And x = the distance of the corresponding isotherm from the plane.

"While r varies from $a/2$ to $b/2$, x varies from 0 to B.

"Since the temperature gradient at the surface of the film is assumed independent of the radius, at this point:

$$dr = dx.$$

"Elsewhere, since *within* the film convection is considered to be negligible, the total heat flux is constant, and since the conducting area is proportional to r and the heat conductivity *at the same temperature* independent of it, the temperature gradient is inversely proportional to r.

"Whence:

$$dr = \frac{r}{\frac{b}{2}} dx. \tag{18}$$

"Since the comparison is between points at the same temperature only, the temperature coefficient of heat conductivity does not enter at all.

"Integrating between limits:

$$ln \frac{b}{a} = \frac{2B}{b}.$$

"Multiplying by b:

$$b\, ln \frac{b}{a} = 2B. \tag{19}$$

Calculation of the Energy Loss from Cylindrical Wires.

From (11*a*)

$$ln \frac{b}{a} = \frac{2\pi}{s}.$$

Substituting in (19)

$$\frac{2\pi b}{s} = 2B \tag{20}$$

or

$$\frac{b}{a} = \frac{\mathbf{s}}{\pi \frac{a}{B}}.$$

But from (11*a*)

$$\frac{b}{a} = \epsilon^{\frac{2\pi}{\mathbf{s}}}.$$

Whence

$$\frac{\mathbf{s}}{\pi \frac{a}{B}} = \epsilon^{\frac{2\pi}{\mathbf{s}}} \tag{21}$$

or

$$\frac{a}{B} = \frac{\mathbf{s}}{\pi} \epsilon^{-\frac{2\pi}{\mathbf{s}}}. \tag{22}$$

From this a curve may be drawn giving a/B as a function of **s**.

The following table gives values of **s** and a/B from which such a curve may be plotted (slide rule calculation).

TABLE II.

s	a/B	**s**	a/B	**s**	a/B	**s**	a/B
0.0	0.0	5.0	.453	10	1.696	30	7.738
0.5	0.735×10^{-6}	5.5	.558	12	2.263	32	8.370
1.0	0.594×10^{-3}	6.0	.671	14	2.844	34	8.995
1.5	0.725×10^{-2}	6.5	.788	16	3.438	36	9.622
2.0	2.752×10^{-2}	7.0	.908	18	4.040	38	10.25
2.5	.0644	7.5	1.032	20	4.645	40	10.87
3.0	.1176	8.0	1.160	22	5.263	42	11.50
3.5	.185	8.5	1.291	24	5.877	44	12.14
4.0	.265	9.0	1.424	26	6.505	46	12.77
4.5	.354	9.5	1.561	28	7.122	48	13.40
5.0	.453	10.0	1.696	30	7.738	50	14.03

If we know the value of B for any gas, that is, if we know the thickness of the film of gas in the case of a plane surface then we can very easily calculate the watts loss per unit of length from a wire of any diameter. The calculation is as follows:

Given.—B, the thickness of film for plane surface; a, the diameter of the wire.

Method.—1. Calculate a/B. 2. Look up the corresponding value of **s** from the above table (or on curve). 3. Look up the values of φ corresponding to the temperature of the wire and to the temperature of the gas some distance from the wire.

Result.—Then **W**, the watts lost per cm. of length of the wire, will be

$$\mathbf{W} = \mathbf{s}(\varphi_2 - \varphi_1).$$

Variation of B with the Pressure, Temperature and Nature of the Gas.

Although the effect of these factors on b, the thickness of the film around a cylindrical wire, would be complicated and difficult to foresee, yet it would seem probable that B, the thickness of the film for a plane surface, would vary in some simple way. The most natural assumption seems to be that B would be proportional to the viscosity of the gas and inversely proportional to its density. For it is the viscosity that causes the existence of the film and it is the difference of density between hot and cold gas (proportional to the density itself) that keeps the film from becoming indefinitely large.

PART III. EXPERIMENTAL.

Calibration of Platinum Wire.

Twenty feet of platinum wire, .020″ in diameter, was especially prepared for us by J. Bishop from the purest platinum.

We specified that it should have a temperature coefficient of electrical resistance of .0038 (from 0°–100° C.) but actually we found it to have only .00350. The purest platinum obtainable from Hereaus has a temperature coefficient of .0039. Nevertheless, we decided that this platinum would fill our needs.

Part of this wire was drawn down, through diamond dies, to the following sizes:

.010, .005, .0027 and .0016 inches.

The wires were annealed and the resistance of three of them was determined at the temperatures 0°, 100° and 445°, and the constants of Callendar's formula were calculated and found to be

$$\alpha = .00350,$$
$$\delta = 1.720.$$

Slight differences were observed between the different wires, but as no very great accuracy was sought it was assumed that the above constants would give the resistance of all of the wires.

In a previous paper[1] the author has shown that above a temperature of about 1100° C. the resistance of platinum no longer follows the parabola of Callendar, but is practically linear. The ratio between the hot resistance and the resistance at 0° C. was calculated from the parabolic

[1] J. Am. Chem. Soc., *28*, 1357 (1906).

formula up to 1300° K., and then continued as a straight line. A few points from the curve obtained are tabulated below.

Ratio of Resistance at T° to Resistance at 273° K.

T	273	473	673	873	1073	1273	1500	1700	1900
R/R_0	1.000	1.688	2.328	2.919	3.463	3.958	4.742	5.273	5.804

The accuracy of this calibration was such that the errors in the temperatures undoubtedly do not exceed 20° at 1300° K. and perhaps 50° at the melting point of platinum.

TABLE III.

Wires Used for Experiments.

The data for these wires are tabulated below.

Wire.	Diameter Inches.	Diameter Cm.	Resistance per Cm. at ° C. Ω/Cm.	Specific Resistance Cm. Cube. Microhms.	Temp. Coef. α, from 0° C.	δ, Callendar Equation.
I.	.00159	.00404	.882	11.26	.0035	1.72
II.	.00272	.00691	.2878	10.80	"	"
III.	.00497	.01262	.0878	11.00	"	"
IV.	.00987	.02508	.0218	10.77	"	"
V.	.02004	.0510	.00572	11.62	"	"

The diameters were found by weighing measured lengths of wire on a sensitive balance, and assuming the density of the platinum to be 21.48. These results agreed well with measurements with a micrometer.

Free Convection from Horizontal Platinum Wires in Air.

A piece of the wire about 40–50 cm. long was held horizontally between clamps in a wooden box open at the side. It was found that very steady readings could be obtained if the wire was merely protected from draughts by placing a few large screens around it. For convenience a box was used. It was about 1 meter long, 30 cm. high and 15 cm. deep. The wire was placed about 10 cm. from the top.

Direct current from a 125-volt line was passed through the wire. The current was measured by a calibrated ammeter. The voltage was measured with a voltmeter, connected to fine platinum wire leads which were welded to the hot wire at points far enough from its ends to avoid the cooling action of the latter.

From the volts and amperes the watts per cm. of length and the resistance were calculated. The cold resistance was measured by a Wheatstone bridge. The resistance at 0° C. was calculated, and the

TABLE IV.

Sample Series of Observations on Free Convection from Pt Wire in Air.

Wire No. II. Diam. .00691 cm. Total length 43.9 cm. Length between voltmeter lead 37.32 cm. Wire horizontal. Room temperature 300° K.

Volts.	Amperes.	Watts / Cm.	Resist. / R at 0° C.	Temp. ° K.
1.59	0.131	.00356	1.13	308
2.72	0.217	.0158	1.16	320
3.92	0.288	.0302	1.27	350
5.00	0.34	.0429	1.37	380
6.80	0.415	.0758	1.53	425
9.40	0.499	.1257	1.75	490
14.35	0.615	.2305	2.17	620
18.9	0.679	.344	2.59	760
25.8	0.771	.534	3.12	945
28.1	0.800	.603	3.28	1010
33.9	0.861	.788	3.66	1155
38.8	0.915	.952	3.95	1275
42.9	0.958	1.12	4.18	1370
45.1	0.98	1.183	4.30	1420
47.2	1.00	1.265	4.40	1460
69.6	1.22	2.275	5.31	1850
72.5	1.235	2.40	5.48	1920[1]

TABLE V.

Wire No.	Diam. Cm.	Length Cm.	Volts.	Amps.	Watts / Cm.	Resist. / R at ° C.	Temp. ° K.	Remarks.
I.	.00404	33.94	12.08	0.25	.089	1.62	450	
			47.9	0.45	.635	3.56	1112	
			70.0	0.53	1.082	4.41	1470	
			102.0	0.63	1.892	5.40	1890	Burnt out.
II.	.00691		—	—	given	above	—	
III.	.01262	36.5	5.52	0.95	.144	1.820	512	
			18.1	1.60	.794	3.54	1105	
			28.5	1.95	1.524	4.56	1530	
			47.5	2.62	3.41	5.65	1995	Burnt out.
IV.	.02508	37.45	3.60	2.30	.221	1.92	545	
			11.12	3.74	1.11	3.64	1145	
			14.5	4.24	1.64	4.19	1375	
			19.1	4.85	2.48	4.84	1650	Burnt out at thin
			23.7	5.42	3.44	5.35	1868	spot.
V.	.0510	44.5	2.19	4.75	.234	1.815	510	
			6.83	8.00	1.227	3.31	1020	
			11.99	10.60	2.85	4.45	1485	
			17.70	13.00	5.175	5.35	1868	Not burnt out.

[1] Burnt out.

ratio of the hot resistance to that at 0° C. was calculated and from this the temperature was determined from the calibration curve obtained as described above.

About the same number of observations were made with each of the other wires. A few only of these, taken at random, are given in the following table:

All the observed values of watts/cm. (87 observations) were plotted against temperature and *smooth* curves drawn as nearly as possible through the points. With two exceptions the maximum deviation of the observed watts/cm. from that of the curve was 3 per cent. and in most cases the deviation was less than 1 per cent. So it is evident that the convection currents were steady and that draughts of air were not influencing the results.

The following data were taken from the smoothed curves as obtained above.

TABLE VI.

Total Energy Losses from Horizontal Platinum Wires in Air (300° K.) in Watts per Cm.

Wire No.	Diam. Cm.	Temp. ° K.							
		500	700	900	1100	1300	1500	1700	1900
I.	.00404	0.11	0.24	0.41	0.61	0.84	1.14	1.54	2.13
II.	.00691	0.12	0.29	0.48	0.72	0.99	1.33	1.79	2.48
III.	.01262	0.13	0.31	0.53	0.79	1.11	1.46	1.95	2.71
IV.	.02508	0.17	0.39	0.68	1.02	1.45	2.00	2.68	3.55
V.	.0510	0.22	0.52	0.90	1.42	2.03	2.89	4.10	5.65

Radiation from Platinum.

The total radiation per sq. cm. of surface from a black body at temperature T is

$$5.32 \left(\frac{T}{1000}\right)^4 \text{ watts.}$$

Or, the radiation from a wire of a cm. in diameter is

$$16.7a \left(\frac{T}{1000}\right)^4 \text{ watts per cm.}$$

Now platinum is far from being a black body. Lummer and Kurlbaum[1] have determined the ratio between the radiation from platinum and

[1] Verh. Phys. Ges., Berlin, *17*, 106 (1898).

that of a black body and found

Temp. ° K.	Ratio Pt : Black Body. Per Cent.
492	3.9
654	6.0
795	7.5
1108	11.2
1481	15.4
1761	18.0

From these data a curve was plotted and the radiation from the platinum wire used in these experiments was calculated as follows:

TABLE VII.

Energy Radiated from Platinum Wires in Watts/Cm.

Wire No.	Diam. Cm.	Temp. ° K.							
		500	700	900	1100	1300	1500	1700	1900
I.	.00404	.000	.001	.004	0.011	0.026	0.05	0.10	0.17
II.	.00691	.000	.002	.007	0.019	0.044	0.09	0.17	0.29
III.	.01262	.001	.003	.012	0.034	0.080	0.17	0.31	0.53
IV.	.02508	.001	.007	.024	0.067	0.159	0.33	0.62	1.06
V.	.0510	.002	.013	.049	0.137	0.323	0.67	1.25	2.15

Subtracting these corrections from the total watts lost in air we get

TABLE VIII.

Energy Conducted from Platinum Wires by Air, or "Convection" Losses in Watts/Cm.

Wire No.	Diam. Cm.	Temp. ° K.							
		500	700	900	1100	1300	1500	1700	1900
I.	.00404	0.11	0.24	0.41	0.60	0.81	1.09	1.44	1.96
II.	.00691	0.12	0.29	0.47	0.70	0.95	1.24	1.62	2.19
III.	.01262	0.13	0.31	0.52	0.75	1.03	1.29	1.64	2.18
IV.	.02508	0.17	0.38	0.66	0.95	1.29	1.67	2.06	2.49
V.	.0510	0.22	0.51	0.85	1.28	1.71	2.22	2.85	3.50

From these data the thickness of the film of air, B, for a plane surface was calculated as follows:

$$\mathbf{s} = \frac{\mathbf{W}}{\varphi_2 - \varphi_1}$$

(φ_1 being taken at 300°).

Then from a curve giving the relation between $\mathbf{s}$ and a/B (equation 22) the corresponding value of a/B was found. From this B was calculated.

TABLE IX.

Thickness of Air Film for Plane Surface Calculated from Table VIII.

Wire No.	Diam. Cm.	Temp. ° K.								
		500	700	900	1100	1300	1500	1700	1900	Mean.
I.	.00404	.27	.43	.43	.47	.56	.47	.40	.25	.41
II.	.00691	.31	.32	.38	.40	.43	.47	.38	.26	.37
III.	.01262	.42	.42	.44	.49	.56	.69	.69	.47	.54
IV.	.02508	.30	.37	.37	.41	.45	.45	.51	.56	.43
V.	.0510	.28	.30	.33	.33	.36	.37	.35	.36	.34
Mean		.31	.37	.39	.42	.49	.49	.47	.38	.41

In drawing conclusions from the above table it should be borne in mind that a small error in the W/cm. will make a very large variation in B, as will be more clearly shown later.

Two facts stand out clearly from the above table:

1. The thickness of the film, B, calculated for a plane surface does not vary with the diameter of the wire. That is, within the experimental error, the expression

$$b \ln \frac{b}{a} = 2B$$

gives the relation between the thickness of the film and the diameter of the wire.

2. The film thickness B is surprisingly independent of the temperature. Considering the possible errors in the temperature measurements owing to the wires not being separately calibrated by resistance, it appears probable that B is independent of the temperature within the experimental error. To see if this is so and to judge the accuracy of the results the watts per cm. were calculated from equation (21) assuming the value of $B = 0.43$ cm. (a weighted mean of the above values of B).

TABLE X.

Calculated Energy Loss by Convection.

$B = 0.43$ cm.

Wire.	Diam.	500	700	900	1100	1300	1500	1700	1900
I.	.00404	0.10	0.24	0.41	0.62	0.85	1.12	1.42	1.74
II.	.00691	0.11	0.27	0.46	0.69	0.95	1.25	1.58	1.96
III.	.01262	0.13	0.31	0.53	0.79	1.09	1.44	1.81	2.24
IV.	.02508	0.15	0.36	0.64	0.94	1.30	1.72	2.17	2.67
V.	.0510	0.19	0.45	0.78	1.16	1.61	2.11	2.68	3.30

By a comparison of Table X. with Table VIII. it will be seen that the differences are relatively small, in fact probably within the experimental error. For example the greatest deviation is with wire III. at 1700°, the calculated power loss being 1.81 watts/cm. whereas 1.64 was found by experiment. This is an error of 10 per cent. but corresponds to an error in the resistance of the wire of 4.5 per cent. or an error in temperature of about 90° at 1700°. In nearly every other case the errors are much smaller than this. The general tendency for the calculated W/cm. for wire V. to be less than the observed may be connected in some way with the fact that the specific resistance of this wire is considerably higher (5 per cent.) than that of the others (see Table III.). An error in the temperature measurements of about 4 per cent. (*i. e.*, 40° at 1300°) from this cause would account for the discrepancy in the calculated W/cm.

Free Convections from Tungsten Wires in Hydrogen.

In a previous paper[1] the relation between power consumption and temperature for tungsten wires in hydrogen was studied. In those experiments the temperatures were determined for the most part from the change in the resistance of the wire and from its known temp. coefficient. In a few cases these results were checked by photometric measurements.

These experiments have now been repeated with much more care and in each case the temperature was determined both by resistance and by candle power except at such low temperatures that the candle power could not be measured. The two ways of measuring the temperature gave nearly identical results. The energy lost by radiation was calculated from the formula

$$\frac{W}{la} = 39.4 \left(\frac{T}{1703}\right)^{4.74},$$

W, watts; l, length in cm.; a, diameter in cm.

This formula has been derived in the course of a careful study of the radiation from drawn tungsten wires in exhausted lamps.

The following table gives the W/cm. loss from tungsten wires in hydrogen corrected for radiation by the above formula. Most of the experiments were made with the wire vertically suspended in a tube about 5 cm. diam. Moderate variation in the size of the tube had little effect.

The results in column marked I. are those previously published.

Column II. gives results obtained by the same observer that obtained the results of column I., but in a different series of experiments.

[1] Trans. Amer. Electrochem. Soc., *20*, 225 (1911).

TABLE XI.

Wire: Drawn Tungsten .0045 Cm. Diam.

Temp. ° K.	Watts per Cm. Observed.			Calculated W/Cm.	Ratio.
	I.	II.	III.	IV.	III./IV., V.
500		0.42		0.48	
700	——	1.10	——	1.11	——
900	——	2.00	——	1.90	——
1100	2.5	2.90	2.2	2.84	0.77
1300	3.5	3.70	2.9	3.9	0.75
1500	4.5	——	3.9	5.1	0.76
1700	5.9	——	5.0	6.4	0.77
1900	7.9	——	6.9	7.9	0.88
2100	10.1	——	8.9	9.5	0.94
2300	13.0	——	11.2	11.2	1.00
2500	17.4	——	16.0	13.0	1.23
2700	24.8	——	24.5	15.0	1.63
2900	36.4	——	39.0	17.3	2.26
3100	56.4	——	60.2	19.4	3.11
3300	96.2	——	88.2	21.8	4.06

In column III. are the results obtained in the recent experiments referred to. At low temperatures they are probably not any more reliable than those of columns I. and II., but at high temperatures (above 2300°) where the candle powers were used for the temperature estimation, the results of column III. are much more trustworthy than those of column I.

The calculated W/cm. given in column IV. were obtained as follows:

For air at atmosphere pressure and room temp. B is equal to 0.43 cm., the weighted mean obtained from Table IX. We assume, for different gases or the same gas under different conditions, that B would vary directly as the viscosity and inversely as the density at the outside surface of the film. At 300° K. the viscosity of hydrogen from equation (2) is 0.496 that of air. The density is .070 that of air. Hence B for hydrogen should be 0.496/0.070 or 7.1 that of air, that is, for hydrogen at 1 atmo.

$$B = 3.05 \text{ cm.}$$

For a wire .0045 cm.

$$\frac{a}{B} = .00145,$$

whence

$$\mathbf{s} = 1.131.$$

The W/cm. (calculated) given in Table XI. are obtained by multiplying this value of **s** by the values of $\varphi_2 - \varphi_1$ for hydrogen (see Table I.)

calculating φ_1 for the temp. 300° K. From the value of **s** by (11*a*) it is found that b, the effective diameter of the film of stationary gas around the wire, is 1.14 cm.

Up to the temperature of 2000 the observed value of W/cm. in columns I. and III. are less than the calculated. This is to be expected from two causes: (1) The gas in the tube is at a temp. above 300° K. which would increase φ_1 and decrease $\varphi_2 - \varphi_1$, and with it, **W**. (2) The walls of the tube would prevent to some extent "free convection" and would tend to increase b, thus decrease **s** and therefore **W**.

On the whole at temperatures below 2300° the agreement is strikingly good in view of the fact that the results are calculated from experiments with platinum wires in air and that no arbitrary constants have been employed.

The increasingly large deviations above 2300° are due to dissociation of hydrogen into hydrogen atoms. This was suggested in the previous paper and has now been amply verified. The results on the measurement of the extent of the dissociation and the heat of the reaction were given in a paper presented before the Washington meeting of the American Chemical Society, December, 1911. These results will soon be published in the Journal of the Society.

Free Convection from Tungsten Wires in Mercury Vapor.

The apparatus used in this experiment is illustrated in Fig. 1. *A* is a glass tube 2.5 cm. in diameter, containing mercury at its lower end which serves to supply the mercury vapor and also to make electric contact with a platinum wire fastened to the lower end of the tungsten wire *W*. The wire *W* about 7 cm. long is welded at its upper end to a heavy platinum wire which is fastened to a steel rod *F* through which the current is supplied. The tube *A* is wound with resistance wire with leads *E–E*. Another coil with leads *GG* is placed around that part of the tube containing the mercury. Asbestos insulation *K* prevents too great heat loss from this lower end whereas a second glass tube *C* placed around *A* serves to prevent heat loss from the central part of the tube. The procedure of the experiments was as follows: The entire apparatus was exhausted to less than 1 mm. pressure. Pure hydrogen was admitted to about 2/3 of an atmosphere pressure and the mercury was raised to boiling by means of the coil *GG*. Then sufficient current was applied to the winding *EE* to prevent condensation of the mercury except above the level of the asbestos placed at *J*. Mica disks *B* served to prevent hydrogen gas from diffusing down into the mercury vapor. Liquid air was placed around the tube, *L*, to dry the hydrogen and to dry out the whole system while exhausted before admitting the hydrogen.

In the first few experiments no mica disks were used, for it was thought that the strong blast of mercury vapor would prevent any hydrogen from diffusing down into the heavy mercury vapor. But it was found that the energy consumption by the wire increased with about the 15th power of the absolute temperature and that the tube *A* which was of lead glass blackened opposite the wire *W* because of reduction of the lead. By using the mica disks the energy consumption became nearly linear and showed no tendency to increase abnormally at high temperatures. But experiments since that time showed that the correction for radiation which we then applied was too large. So the results obtained with our new values for radiation do show a distinct tendency to increase at very high temperatures. However, this is believed to be due entirely to minute traces of hydrogen which did make their way down through the mercury vapor. In fact in several trials, even with the mica disks, the tubes showed signs of blackening due to lead reduction.

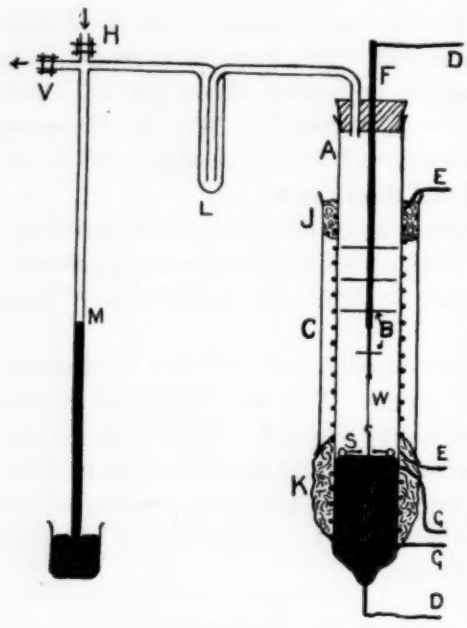

Fig. 1.

Convection from Tungsten Wire in Mercury Vapor.

Temp. of Wire ° K.	Watts per Cm.		Convection.	$\frac{B}{\text{Cm.}}$	Watts/Cm. Calculated.	
	Total.	Radiated.			$B = .0784$.	$B = 0.41$.
1500	0.61	0.13	0.48	.083	0.487	0.15
1700	0.90	0.26	0.64	.072	0.624	0.19
1900	1.24	0.45	0.79	.074	0.777	0.24
2100	1.71	0.76	0.95	.077	0.943	0.29
2300	2.29	1.19	1.10	.084	1.125	0.34
2500	3.04	1.74	1.30	.082	1.315	0.40
2700	4.24	2.54	1.70	.055	1.52	0.46
2900	5.82	3.47	2.35	.034	1.74	0.53
3100	7.74	4.64	3.10	.022	1.97	0.60
3300	9.94	6.00	3.94	.016	2.21	0.67
3500	12.37	7.62	4.75	.013	2.46	0.75

Experiments will probably be undertaken with mercury vapor in the absence of foreign gases to verify this conclusion and obtain more accurate data on the energy loss in mercury vapor.

The following tables gives the results of the final experiment with mercury vapor at atmospheric pressure and a wire of .0069 cm. diameter.

The values of B are calculated as in the case of convection in air. The average value of B up to about 2700° is 0.0784 so this value is used as a basis for calculating the watts/cm. as in next to the last column. It is seen that the agreement between the observed and calculated values is excellent up to about 2700°, but that above this the energy loss is much greater. This is probably due to traces of hydrogen as mentioned above.

If we assume that for different gases the thickness of film, B, for a plane surface should be proportional to **h** and inversely proportional to the density then we calculate that B should be 0.41 cm. For at 600° K. the density of mercury vapor is 3.46 times that of air and its viscosity is 3.27 times that of air. The watts/cm. calculated on this basis are about 69 per cent. too low. It is possible however that the blast of mercury vapor may have caused a greater loss of energy from the wire than would have occurred with "free convection."

At any rate the order of magnitude of the results is right and up to 2700° K. there is no perceptible temperature coefficient to the value of B.

Summary and Conclusions.

It has been shown that:

1. The loss of heat from wires by free convection takes place exactly as if there were a film of stationary gas around the wire, through which the heat is carried entirely by conduction.

2. The thickness of the film is independent of the temperature of the wire, but probably increases with increasing temperature of the surrounding gas.

3. The loss of heat from very small platinum (also copper) wires by radiation is negligibly small up to temperatures of several hundred degrees.

4. The thickness of the film of gas varies in a simple way with the diameter of the wire, namely,

$$b \ln \frac{b}{a} = 2B,$$

B being a constant for any gas, b diameter of film of gas, a diameter of wire.

5. The rate of convection of heat from any wire is equal to the product of two factors, one the shape factor **s** involving only the diameter of the wire and the constant B (for any gas); and the other, a function φ of the heat conductivity of the gas.

Thus if **W** is the energy loss from wire in watts per cm., then

$$\mathbf{W} = \mathbf{s}(\varphi_2 - \varphi_1),$$

where **s** may be found from the equation

$$\frac{\mathbf{s}}{\pi}\epsilon^{\frac{-2\pi}{\mathbf{s}}} = \frac{a}{B}$$

and

$$\varphi = 4.19\int_0^T \mathbf{k}dT.$$

k is the heat conductivity of the gas at the temperature T in cal./cm. ° C.

φ_2 is taken at the temperature (T_2) of the wire, and φ_1 is taken at the temperature (T_1) of the atmosphere.

6. Tables are given by which curves may be plotted showing the relation between φ and T and between a/B and **s**.

7. The fact that B is found to be independent of the temperature is a strong indication that Sutherland's formulæ may be applied to the heat conduction of gases up to extremely high temperatures.

In a subsequent paper the author will show that the formulæ here developed agree extremely well with Kennelly's results on the "Convection of Heat from Small Copper Wire," that for air the thickness of film B varies inversely as the 0.75 power of the air pressure and that for forced convection B varies inversely as the 0.75 power of the wind velocity. It will also be shown that a similar relation holds for the value of B when the temperature of the atmosphere around the wire varies from 90° up to 800° K.

Several experiments will also be described in which the presence of such a "stationary" air film is demonstrated. The thickness of the film has been determined by direct measurement and the temperature distribution around the filament has been studied with care.

The author wishes to express his indebtedness to Mr. S. P. Sweetser, Mr. H. Huthsteiner and Mr. E. Q. Adams for most of the experimental work in connection with this investigation.

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ON THE CONDUCTION OF ELECTRICITY AT CONTACTS OF DISSIMILAR SOLIDS.

By Robert H. Goddard.

Introduction.

THE fact that the resistance to the flow of current across the contact of dissimilar solids depends upon the direction of the current was first observed by Ferdinand Braun[1] in 1874, with metallic sulphides against metals. Braun showed later, 1877–8, that the effect was not due to counter E.M.F. of polarization, as the sulphide suffered no change in weight. Also, current from the secondary of an induction coil passed simultaneously decreased the resistance in both directions.

The more recent contributions to the subject have been inspired, in most cases, by the application of such unilaterally-conducting contacts, usually called "crystal rectifiers," to the detection of electromagnetic waves. The name comes from the fact that contacts having this property are usually those between a metal and a crystalline substance. Many such crystals are known. Among those which have been most carefully studied are the silicon-steel, carbon-steel, and aluminium-tellurium rectifiers of L. W. Austin.[2] The first gave phenomena, very reproducible below 0.2 volt, A.C.; the direction of the rectified current being from steel to silicon, except with one specimen which gave opposite rectification for all points on the surface. In every case the thermo-E.M.F. was opposite to the rectified E.M.F.

The carbon-steel rectifiers were made by placing a steel needle in contact with a cored arc-light carbon. Graphite was found unsatisfactory. A lamp filament against a light carbon also furnished a satisfactory rectifier. The phenomenon was not, however, regular with direct current. The rectified current was from steel to carbon.

The aluminium-tellurium rectifier, discovered previously by Austin,[3] exhibited a marked peculiarity. For low voltages, up to 0.6 volt, 8.0 amperes, the rectified current was in the direction of the thermo-E.M.F.; *i. e.*, Al to Te; whereas above this voltage, the rectified current was in the opposite direction, and increased with increasing voltage. Large contacts, such as a No. 20 aluminium wire melted into a block of tel-

[1] Ferdinand Braun, Pogg. Ann., 153, p. 556, 1874.

[2] L. W. Austin, Bull. Bur. Standards, 5, 1, pp. 133–147, 1908.

[3] L. W. Austin, Phys. Rev., 24, pp. 508–520, 1907.

lurium, gave marked unilateral conductivity with direct, but unsatisfactory rectification with alternating, currents.

An extensive series of experiments has been undertaken by G. W. Pierce. The first piece of work[1] was on the carborundum rectifier. The resistance of this substance is much higher than that of those just described, so that a rectified current of the order of 10^{-3} amperes requires an E.M.F. of 20 volts. With a pressure on the crystal of 500 grams, one specimen gave a rectification of 4,000 : 1. On increase of pressure the resistance fell in both directions but the rectification, *i. e.*, the ratio, decreased. There was still some rectification, however, even when the crystal was driven well into the electrode. Best results were obtained when one of the surfaces of the crystal was platinized, to give low resistance, the rectified current then being in the direction of crystal to metal. With a current of ½ ampere, the rectification was but 1.6 : 1.1, the crystal grew hot, and the contact surfaces luminous. The temperature coefficient of resistance of carborundum resembles that of a salt solution more than that of a metal.

An hysteresis effect was observed, apparently due to a slow building-up of the current, which disappeared after a few reversals—the current on rise of E.M.F. being less than on return to zero. An attempt was made to observe a back E.M.F. The rectifier was connected alternately, 120 times a second, with a source of potential of 35 volts, and a capillary electrometer. A persistent but very small reading, 0.002 volt, was indicated.

The second piece of work[2] was performed with certain minerals—brookite, anatase, and especially molybdenite. For each of these the rectified current was from metal (usually copper) to crystal, and of the order of 0.01 ampere for 10 volts. The extent of the rectification depended upon the circumstances of contact, as regards position on the surface of the crystal, and pressure at the point.

Of particular interest were the experiments with molybdenite, undertaken to show, by oscillographic records, the existence of a counter E.M.F. existing for a short period of time. The apparatus consisted of a Braun tube, the luminous spot of which was focused on a sensitive film on a rotating drum. This drum was driven in synchronism with the current which passed through the rectifier and the deflecting magnets of the Braun tube. The drum was revolved until successive exposures had combined to give a sufficient intensity to the film. These oscillograms showed that the rectified cycles led their respective voltage-phase

[1] G. W. Pierce, Phys. Rev., 25, pp. 31–60, 1907.
[2] G. W. Pierce, Phys. Rev., 28, pp. 153–189, 1909.

cycles at three positions. But these could be obtained by calculation, from the resistance and inductance of the circuit. In fact, no departure in amplitude or phase existed between the rectified cycle and the voltage-phase (applied) cycle that was not accounted for by the inductance of the oscillographic apparatus, or by the current-voltage curves of the rectifier with steady currents. In other words, if there were any terms contingent upon heating or other effects which involve an integral of a function of the current with respect to the time, this integral attained its final value in about 1/6,000 second, corresponding to about 1 mm. on the original photograph.

In a further piece of work,[1] Pierce examined the rectifying properties of iron pyrites. This substance had been studied previously by Braun, who found that the difference in the conductances in the two directions increased with increase of current; and with continued passage of the current, the larger conductance decreased. Pierce found this only with currents large enough to heat the contact.

The oscillograms, like those taken with the molybdenite rectifier, showed that the current through the rectifier had the same phase and amplitude it would have if the rectifier were replaced by a resistance producing the same amplitude, *i. e.*, there was no apparent integrative action. This rectifier showed the irregular action manifested by all the solid rectifiers previously investigated, namely, that for some adjustments of the contact, the greater current was from copper to crystal, whereas for other adjustments, *e. g.*, with a different pressure, or at a different point on the crystal, the greater current was from crystal to copper. With fixed adjustments, the current and E.M.F. were constant.

A study of the galena rectifier has been made by A. E. Flowers.[2] When the E.M.F. is gradually increased from a low value, "break-downs" occur; *i. e.*, the current jumps suddenly to a higher value. If the E.M.F. is further increased, a large jump of current eventually occurs, the metal point sinks into the galena, and rectification is destroyed. These break-downs occur more frequently if the E.M.F. is reversed at each increase, and the contact will stand a rather high E.M.F. if it is removed temporarily, as soon as the breakdown occurs.

In confirmation to Pierce's observations, certain parts of the galena crystal were found to be non-rectifying. Further "a non-rectifying surface was often found to have others beneath and parallel, when layers were split off, but scratching or scarring a surface usually spoiled more or less completely its rectifying properties." Heating destroyed the

[1] G. W. Pierce, PHYS. REV., 29, pp. 478–484, 1909.

[2] A. E. Flowers, PHYS. REV., 29, pp. 445–560, 1909.

effect, although it was sometimes regained by further heating, disappearing again as the temperature was still further increased. The effect did not depend upon the metal at the contact.

The author emphasizes the time taken to build up the current on closing the circuit, observed with some crystals, especially on heating. It was found that an artificial rectifier could be made by allowing sulphur to burn on the end of a copper wire for a moment, and afterward placing this sulphur against lead (brass was unsatisfactory) and reversing a current through the contact a few times.

Few theories of the foregoing phenomena have been suggested. The effects were first thought to be of thermoelectric origin but Austin and Pierce showed that heating could not account for the magnitude of the effects observed. Pierce[1] considers that all rectifiers come under more or less the same class of phenomena, and that there may be some connection between thermo-E.M.F. and rectification, as all rectifying crystals have large thermo-E.M.F.'s against the common metals. Flowers concludes that the effect, with galena, is due to electrochemical deposition of a resisting film.

Allied Phenomena.

Closely related to the crystal rectifier is the electrolytic rectifier—a fine platinum wire touching the surface of an electrolyte. Although the contact area is of the same order, there are two marked differences; oscillograms made by G. W. Pierce[2] show evidence of a positive E.M.F., for about 1/1,500 second, greater than the E.M.F. immediately following; further, for best results, a steady current should be superposed on the alternating current to be rectified. Austin[3] considers that heat is one of the factors, with, probably, chemical action and electrostatic attraction across the gas film.

The aluminium valve, or rectifier, which consists of a cell containing one of certain electrolytes, one electrode being an aluminium plate, is more amenable to experiment than the rectifiers previously described, owing to its size. The hindrance to the passage of the current has been shown[4] to be due to back E.M.F. This is produced slowly on a fresh plate, 10 minutes being required to obtain the full valve effect at 15 volts. Increase of temperature decreases this E.M.F. Careful experiment[5] has shown that the back E.M.F. together with the drop due to ohmic resistance is equal to the total impressed voltage even when the latter is 20

[1] G. W. Pierce, Phys. Rev., 29, pp. 478–484, 1909.
[2] G. W. Pierce, Phys. Rev., 29, pp. 56–70, 1909.
[3] L. W. Austin, Bull. Bur. Standards, 2, pp. 201–224, 1906.
[4] S. R. Cook, Phys. Rev., 15, p. 23, 1904.
[5] S. R. Cook, Phys. Rev., 20, pp. 312–321, 1905.

or more volts. On removing this applied voltage, the counter E.M.F. falls off to about half its value in 10 seconds.

There are two suggested explanations for the low resistance of the valve when aluminium is cathode. Guthe[1] suggests that hydrogen ions are liberated between the film and the metal, and these can pass through the more or less solid film of Al_2O_3 on the metal, whereas, when the current is in the opposite direction, the large negative ions from the solution cannot penetrate this film. Schulze[2] considers that the solid film merely serves to hold a gas between it and the metal. Electrons from the metal can pass readily through this gas whereas the large negative ions from the solution meet with resistance. This view is more or less supported by experiments made under pressure[3] which show that the rectification becomes less, temporarily, under pressure. When the gas is condensed, there should be less distance for the large ions to travel.

Many coherer phenomena suggest strongly that films play an important part in conduction at small contacts. This is very evident in some cases. For example, very sensitive coherers are formed[4] by lead in contact with *oxidized* copper, or copper alloy. Eccles[5] has advanced the theory that the action of iron-mercury, and oxidized iron-iron coherers depends entirely on the heating of the film of oxide by the electrical oscillations and the current due to the applied p.d. By developing the theory mathematically the necessary results are shown to follow. Further, it has been found[6] that a platinum wire placed upon two others coheres, if an oscillatory spark is set up in the neighborhood. The same effect may be produced with a broken carbon filament in an incandescent lamp globe, provided a considerable resistance is placed in series. The coherence of the platinum wires may also be produced by heating each junction to a red heat.

In certain other cases, the rôle of the film is not so evident. For example[7] a tantalum wire, 0.05 mm. in diameter touching mercury forms a very sensitive coherer, which cannot be made permanently to cohere. Further, Shaw and Garret[8] have found that when a coherer formed of two copper wires touching each other is made to cohere by a spark some distance away, the wires if separated (requiring a small but measurable pull) and held apart for a few moments will not recohere when

[1] Guthe, PHYS. REV., 15, p. 327, 1903.
[2] Schulze, Ann. der Physik, 28, p. 787, 1909.
[3] Carman and Balzer, PHYS. REV., 30, pp. 776–781, 1910.
[4] M. Hornemann, Ann. der Physik, 14, 1, pp. 129–138, 1904.
[5] W. H. Eccles, Phil. Mag., 19, pp. 867–888, 1910.
[6] Majoli, N. Cimento, 10, pp. 552–585, 1905.
[7] L. H. Walter, Proc. Roy. Soc., Ser. A, 81, pp. 1–8, 1908.
[8] Shaw and Garret, Phil. Mag., 8, p. 164.

placed together again, but will do so if the current be reversed. The wires may again be separated and the action repeated several times.

Study of Various Contacts.

In the present investigation it seemed advisable to try a number of rectifying substances against various metals, in order to see if any general conclusions could be drawn. The apparatus consisted simply of a source of E.M.F. of one or two volts, connected through a small resistance to a milliammeter and a switch which served to reverse the current passing

Substance.	Greater Current Flows from —		Conductances Diverge.		Conductances Approach.	
			The More Rapid Change is the—			
	Metal to Crystal.	Crystal to Metal.	Rise.	Fall.	Rise.	Fall.
C	Al Fe	Pb Si			Si	
Te		Mg Al Zn Cu Fe Ag Sn Pb Pt Si Galena	Mg Al Zn Pb Ag Galena	Cu Pt Si		Na
Si	Al Zn Cu Fe Sn Pb Pt		Pb Pt	Al Zn Cu Fe Sn		
Galena	Cu Fe Pb Pt	Al Sn Ag Si Zn		Al Zn Cu Fe Pb Pt		Cu Si
Magnetite	Zn Pb Pt Te	Al Cu Ag Si		Pb Te Si		Zn Cu Pt

through the rectifier. The drop across this switch was measured by a voltmeter with a range of three volts. Direct current was used in order to bring out any gradual change that might appear while the current was being applied. Where there was uncertainty regarding the direction of the rectified current, a number of contacts were made to determine the general direction.

The result of these experiments is given in the following table, in which certain general tendencies are apparent. The conductances, in most cases, grew farther apart the longer the current passed, the rise being more rapid with some metals and the fall with others, as the table indicates.

While the current was passing the conductances usually changed together; *i. e.*, while one was rising or falling, that in the opposite direction was rising or falling, as could be seen by sudden reversals. This was not always true, as one conductance sometimes remained stationary. Usually the conductance in the direction which had undergone greater change recovered the faster. Scraping a metal to remove possible oxide sometimes increased the mean conductance but decreased the difference.

Permanent Changes of Conductance.

The gradual changes that have just been described are indicative of something like a change of structure at the contacts, due to the passage of the current, and an attempt was made to learn if the conductance of the contact was the same after current had passed in either direction. To test this point, rectified currents of the order of 1×10^{-2} amperes were passed through the contact, which could be immediately connected is series with a galvanometer and a high resistance, so that a current would pass of the order 1×10^{-5} amperes, which did not produce rectification.[1]

The current due to thermo-E.M.F. was eliminated by reversing the current through the contact and taking the mean value. The difference in the deflections, after the larger current had passed in one direction or the other, varied up to about 30 per cent. of the lesser, depending somewhat on the circumstances of contact. The deflections were for the most part steady, and were, for most substances, greater after the current had passed from metal to crystal, as the following table will show.

That these changes of resistance, indicated by galvanometer deflections, did not take place instantly was shown by passing the larger current

[1] Throughout this paper, excepting the part that deals with the oscillographic study, the "rectification" was measured by applying a direct current, first in one direction and then in the other direction, the time of application being long enough to take a reading of the current.

in one direction, then noting the deflection with the smaller current—for example Te to Fe_3O_4, deflection 13.8—then "making" the larger current in the opposite direction for very short intervals, by letting the ends of two wires touch while moving rapidly past each other—giving, successively, deflections, 13.2, 12.6, 12.0, the last being the same as that obtained for this direction previously. In some cases, for example, PbS, Zn, the deflections after long exposure to current were less than after a shorter exposure.

Substance.	Deflection Greater After Current has Passed from	
	Metal to Crystal.	Crystal to Metal.
Te	Fe	Al
	Pb	
	Pt	
	Si	
	Galena	
Si	Al	Zn
	Cu	Pb
	Fe	Pt
	Si	
Galena	Al	Pt
	Zn	Si
Magnetite	Al	Zn
	Fe	Te
	Pb	Galena
	Pt	
	Si	

Before the larger current was first applied, the deflection was usually smaller than afterward, and in certain cases was not steady, there being a slow rise or fall of deflection irrespective of whether the small current were on or not. The effect was not of a very definite nature and seemed to depend upon the circumstances of contact. Most of the substances and metals gave steady deflections; those showing a fairly certain rise and fall respectively were: Fe_3O_4, Pb; Fe_3O_4, Si; PbS, Te; Si, Si; and Te, Pt; Fe_3O_4, Pt; PbS, Zn. The effect is very similar to a spontaneous rise observed by the writer in studying the conductivity of powders,[1] namely, for powdered BaS.

Effects with Large Currents.

In considering the general effects by currents of from 0.5 to 9 amperes, it will be convenient to call the direction of current from metal to crystal,

[1] R. H. Goddard, Phys. Rev., 28, p. 411, 1909.

A, and the reverse direction, *B*. In most cases the current in the direction *A* showed the greater irregularity, the current in the direction *B* being perfectly steady in some experiments. An exception was C, Fe_3O_4, for which the current in direction *A* took steadily the largest value *B* attained in its frequent jerks. These irregularities for *A* were of a definite kind, with some contacts. For example, with galena against Cu, Ag, Pb, Pt, and once with Te, Pt, the current kept falling gradually and then rising with a jerk. With Si, Zn; Si, Pb; and PbS, Ag, these irregularities were accompanied by acoustic effects. In the first two contacts a hissing noise accompanied the passage of current in the direction *A*, while there was silence for *B*, except for occasional clicks. The PbS, Ag contact emitted a musical trill for the direction *A*. Also, with other contacts, there was occasionally a click on opening the circuit, and on reversing.

During the passage of a large current, there was visible sparking for the direction *A*, most noticeable with Te, Al; Te, Mg; Te, Zn, but lacking with Te, Ag; and Si, Al. Also, if the contact was glowing, the color was usually brighter for the direction *A*, especially with Si, Al; Si, Pt; Si, Zn; Te, Zn; Te, Al; but duller with Fe_3O_4, Al; Fe_3O_4, Zn. The portions of some substances close to the contacts showed colored deposits after the passage of considerable current. With Si, Zn the color was yellow, with C, Al, white, and with Fe_3O_4, reddish.

The direction of greater current, *i. e.*, of rectification, changed in many cases when the current was increased to 0.5 ampere or more, the general tendency being to change from the direction *A* to *B*. Tellurium, for which the rectification is in this direction, gave no change on increase of current, with any metal. Silicon exhibited this change with Al, Ag, Fe, Zn, and Pt, with currents equal to and greater then 0.45, 1.3, 0.50, 0.55, and 0.50 amperes, respectively. Different settings gave other, but not widely different, values. In the case of Zn, at 1.7 amperes, a high resistance state occurred—equivalent to the establishment of a high resistance at the contact. The current fell to 3×10^{-3} ampere, and the direction of rectification changed to *A*. Magnetite against Al, Zn, Pb, and Pt, showed similar change of direction for currents from 0.5 to 0.8 ampere. The effect was not observed with Cu. Galena gave results of less certainty, although the direction was *B* with all the metals, Mg, Al, Zn, Cu, Fe, Sn, and Pb for two amperes.

On some occasions, immediately after reversing from the direction of larger current, the current remained large for a second or so, then falling to a low value. This was noticed at times with PbS, Ag; Te, Al; Te, Cu; Si, Pt; and Si, Zn. This lag lasted longer, the longer the current

had been maintained before reversing. The lag occurred in both *A* and *B* directions, for different substances; and the conductance fell from the value just preceding, in some cases, and rose to a higher, in others.

Often, when several amperes were passing, the current would be reduced suddenly to but a milliampere or so, at 20 volts, with the substances still in contact, and the rectification sometimes still persisting. This state, independent of the direction in which the current had been flowing, was permanent, as the substances could be pressed gently together without destroying the high resistance. The phenomenon was marked with Si against Mg, Al, Zn, Cu, and Pt; also with magnetite against Al, Zn, and Cu.

The rectification was less for small currents, after the passage of large currents, than before.

Microscopic Examination During Passage of Large Currents.

Certain light effects were observed to take place coincidently with jerks and irregularities observed with the current-measuring instruments. The most striking phenomena were obtained with silicon. A microscope of 50 diameters magnification was used. The appearance, with Pt, may be seen from Fig. 1. For the direction *A*, at 1.8 amperes and 3.8 volts the tip of the platinum wire, *a*, was dim, while the adjacent Si, *b*, was bright. On reversing, *b* became less bright, while *a* grew nearly as red as *b* after the lapse of about 0.5 second. The voltage simultaneously rose from 3.5 to 3.8 volts, the current remaining closely the same. This was repeated at least a dozen times. With increase of current, the

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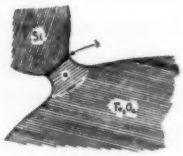

Fig. 2.

contact "broke down," and gave about the same current for each direction. With another setting, Si, Pt gave no rectification although the contact appeared brighter for the direction *A*. On the other hand, certain contacts gave rectification but no light; *e. g.*, sometimes Si, Zn and Te, Pt.

The contact Fe_3O_4, Si had the appearance shown in Fig. 2. For the direction *A*, with current of 1.2 amperes at 11 volts, the region *a* became red, the light spreading quickly from the junction, *b*, between the Si and Fe_3O_4. On reversing, blue sparks appeared for an instant along

the line *b*, when the current fell to 6×10^{-3} amperes at 24 volts. These changes could be repeated. Curiously, there were sparks for an instant on closing the circuit in the direction *B*, and also in the direction *A*, even if the circuit was opened for five minutes before reversing.

If, after breaking the circuit in the direction *A*, connection was made with a milliammeter, a sudden throw of 50 divisions was obtained, falling at once to 15, and thence slowly to about 2. A very short application of the larger current gave a throw indicating 15 milliamperes—the fall being more gradual. Increase of the larger current destroyed the rectification.

A contact of Fe_3O_4, Al showed blue sparks for the direction *A*, followed by redness of the metal. For current in the opposite direction, the metal was less bright, and the mineral at the contact glowed white hot. In one experiment, with a current of one ampere, a bright spot moved slowly around, a short distance from the center of the contact. With Pt, the current for *A* was fairly steady, while that for *B* was unsteady, and lowest during sparking.

Tellurium, with Mg and Al, gave continuous sparking for the direction *A*, and but a single spark on closing the circuit in the direction *B*. With Pt, however, asymmetry was obtained without sparking even at 1.5 amperes. Arc-carbon gave less definite results. Al generally gave sparking and less current for the direction *B*. Sometimes with Fe there was sparking only for current in the direction *B*. At other times there were occasional flashes for both directions. Carbon against Si, with currents of two amperes or more, gave intermittent sparking for both directions, the direction of greater current being uncertain. The direction was also uncertain for C, Fe_3O_4, but although there was not continuous sparking for the direction *B*, the sparks were usually larger for this direction of the current.

With PbS the light did not appear continuously, and experiments made to determine the light effect were therefore uncertain. The sparking usually took place, however, in the direction *B*.

In a number of special experiments, the effect of large currents could be seen without the aid of a microscope. A small cube of PbS, placed between the ends of two No. 50 aluminium wires grew red hot and showed blue sparks where the current entered, the metal being redder on this side, also, when a current of two amperes was passed through. Increase of current made the sparking more energetic, and when 4.5 amperes were reached, the high resistance state previously mentioned was produced. A small piece of Fe_3O_4 placed between the wires behaved in a similar manner,

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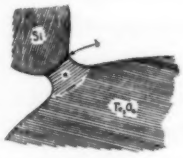

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except that it was more difficult to keep the current flowing. In a similar experiment with Si, the element grew red hot, with a much brighter point where the current entered.

A peculiar effect was also obtained when two pieces of silicon, one or two cm. long, where placed in contact and a current of one or two amperes passed through the junction. The piece on the negative side, even if thinner, was brighter from the contact to a cm. or more away. A small blue spark appeared on separating the two pieces, and it was found impossible to produce an arc. After the experiment the pieces were fused together. The effect disappeared when sufficiently large currents, *e. g.*, 25 amperes, were passed through the junction. This was very different from the behavior of two pieces of Fe_3O_4 in contact, in which there was usually no sparking, or difference in color on reversing. Once, when rectification appeared at 3 amperes, with the greater current in the direction *A*, the contact appeared redder as a whole when the current passed in this direction.

Effects in High Vacua.

The foregoing experiments, while suggesting electrolytic, or allied, action, at least made certain the necessity of performing the experiments with chemically clean surfaces. For this purpose a number of methods were tried. First, an attempt was made to clean the substance by using it as a cathode in a discharge tube, and causing it to give off a cathode deposit. The result was unsatisfacotry, as the effect was uncertain—a result which is in accord with the literature of the subject. Melting the substance by passing a heavy current through a piece in which was a narrow portion, was found to present too many difficulties. Cutting the specimen by means of cut-nippers operated through a ground joint was found too complicated to be practical.

The method finally employed was a simple one, and may be understood by an examination of Fig. 3 (*a*). The first step in the procedure was to exhaust the system by connecting the ground joint, *J*, with a Gaede mercury pump. When the highest vacuum the pump would give (without freezing mixtures) was attained, tested qualitatively by the discharge tube, the cock was closed and the system removed from the tube leading to the pump. In the first experiments, the cock was not used—the tube being sealed off—but the vapor of the vacuum wax used was later found not to give different results from those obtained with sealing. The substances studied had previously been set in solder, if poorly conducting, and placed in a holder, as (*b*), Fig. 3. In the figure is shown a metal, filed into the required shape, and held in place by a screw. This holder,

containing a piece of iron wire (shown dotted), could be moved from the outside by a 6-inch permanent horse-shoe magnet; and as this wire was placed off center, the holder could be rotated through any angle. A continuous electrical connection between the holder and the electrodes in the end of the tube was secured by soldering to them a closely-wound coil of No. 48 bare copper wire, about 1/8 inch in diameter. The holder could be moved with ease where desired, and as many as four specimens could be kept in the bulb, B_1, without serious entanglement.

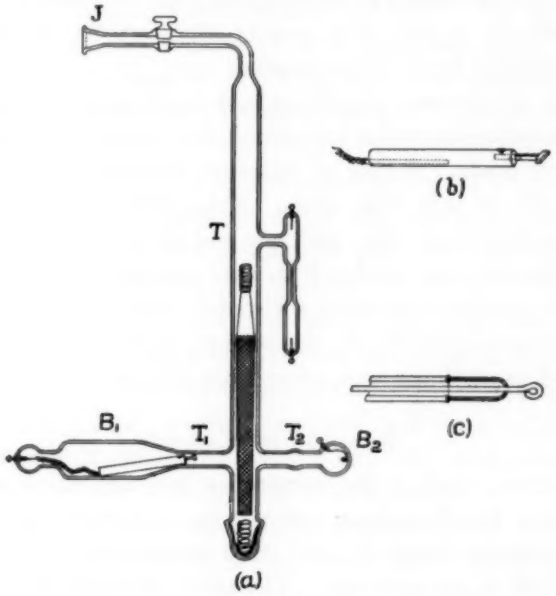

Fig. 3.

The specimen could be cleaned by filing, in which case it was allowed to rest against the file, the holder being in the tube, T_1, and the whole system was shaken back and forth to permit motion of the file relatively to the specimen. The file, of circular section, was prevented from breaking through the tube by a spring fastened to the top, and another spring, one end of which was pulled out, bent into the form of a U, and placed in the tube with the ends of this U pressing into two dents in the wall of the tube. This served to keep the spring in place.

Another method of securing a fresh surface, more satisfactory than by filing, was to break off the end of the specimen by dropping the file upon it as it protruded from the side tube, T_1. This was facilitated by filing a small indentation in the specimen near the holder. Metals were bent back and forth until they broke, by turning the holder through 180°

before each impact. In this way, with a soft metal like aluminium, a clean surface 1 mm. square could be obtained. Of course, before placing specimens in contact, the tube T was inverted so that the file did not hinder passage from T_1 to T_2. In the figure is shown a small bulb, B_2, containing tellurium in contact with a platinum wire which served as electrode. Owing to the comparatively low melting point of tellurium, it could be melted, in vacuo, through the glass. Substances which had to be broken or filed were contained in another bulb, similar to B_1, which was fastened to the tube, T_2, after B_2 had been removed. To get at any holder or specimen it was, then, merely necessary to cut off the tube at the point where the letter T_2 is situated.

In order to use, in some experiments, a much larger current than ordinary vacuum-tube electrodes will stand, the special electrodes shown in Fig. 3 (c) were made. A ring of platinum foil was fastened to the glass tube by means of soft blue glass. This platinum was then copper-plated, and a short lead tube, into one end of which a stout copper wire had been soldered, was soldered to the coppered platinum. Such an electrode was capable of holding a Crookes vacuum, and the amount of current was limited only by the size of the copper wire. This method of soldering lead to platinum was taken from Strasser.[1]

RESULTS IN VACUO.

The substances used in the apparatus just described were Mg, Al, Fe, Pb, against Te, Si, galena, and natural graphite. In the open air, Te and the common fused Si gave good rectification for each metal, in directions B and A, respectively. The effect was strongest with Mg, Al, and Fe. With considerable pressure on a clean Mg surface, Te gave once a small preponderance of current in the direction A. The other substances, galena and natural graphite, gave rather uncertain action at best—the currents in the two directions often being equal—but such rectification as was obtained was usually in the direction B except with PbS, Al and PbS, Pb. The thermo-E.M.F. of these metals was from carbon to metal through the junction. Two kinds of silicon were used: the common fused silicon and some pure crystals, obtained from Eimer and Amend and Bausch and Lomb. The former always gave rectification in the direction A, while some crystals gave rectification nearly always in the direction B. The pure crystals were about 3 mm. long and not more than 0.3 or 0.5 mm. in thickness. The fused silicon was broken into pieces of about this size, and both set in solder. The thermo-E.M.F. for both kinds of silicon was the same; *i. e.*, Al to Si through the junction.

[1] B. Strasser, Ann. der Physik, 31, pp. 890–918, 1910.

With currents and voltages of from 10 to 50 milliamperes and 1 to 3 volts, the following effects were observed in vacuo. Tellurium showed the same action with all the metals tried. Before the metal had been filed, the rectification was the same as in air. Afterward, the currents were exactly equal for a given contact and for those in the immediate neighborhood. There was often a slightly greater current for A, the direction opposite to the rectification in air, giving rise to an E.M.F. difference of 0.01 to 0.04 volt, *in the direction of the thermo-E.M.F.* This held good at 40 or 50 milliamperes or more. For some contacts there was rectification in the direction B, of the order of 5 or 10 per cent. of the total current. Whenever a part of the metal which had not been filed or broken touched the tellurium, marked rectification appeared. The possibility of there being a short circuit was eliminated by touching the platinum wire leading to the tellurium, when the current was very much increased. Experiments in which the tellurium was broken or melted, and the metals broken or filed, all gave the same results. This held good even when the contact was one of considerable resistance. The only metal that gave uncertain action at times was aluminium. Magnesium, on the other hand, gave at all times consistent results. The probable reason is that the former contained traces of silicon, for on dissolving it in aqua regia, a small brownish residue remained, insoluble in hot aqua regia or in hot dilute nitric acid. The magnesium, on being dissolved in hydrochloric acid, gave no visible residue.

The pure silicon gave rectification in direction B to a small extent, and at times gave none at all, whereas the fused silicon usually gave considerable rectification in the direction A, very rarely giving as low a difference as 0.1 volt, and never giving the same current for the two directions. The resistance, also, was usually above that for the contacts with pure silicon. The test with pure silicon was difficult, as it was hard to break off the ends of the small, needle-like, crystals without making the fracture close to the surface of the solder.

Rectification with galena was uncertain, as in air, but more current was obtained in the directions A, B, and A, with Al, Fe, and Pb respectively. With graphite there was no rectification with any metal, save for occasional slight differences in either direction. In all the foregoing experiments, the tests were made with slow reversals.

Some of these experiments were so suggestive of an action due to a resisting film of oxide, especially those with tellurium, that experiments with melted tellurium were carried out in air, as a check upon the work. When a current of 2 amperes at 10 volts was passed through tellurium, melted in a quartz tube, with Pt and Al electrodes the current quickly

fell—when the direction was that of higher resistance—to about ½ ampere. On opening the circuit and closing it again, the value was still ½ ampere, but if the circuit was opened, and 1.5 volts applied in the same direction, the current was too small to give a readable deflection; *i. e.*, < 0.0002 ampere. On reversing, however, the deflection grew slowly until it reached 8×10^{-3} ampere. The large current, passed in the opposite direction, resulted in a deflection at once, on applying the smaller E.M.F. in the same direction.

When the quartz tube was placed in a thermostat, and the aluminium wire broken off under the surface of the melted tellurium, the results were not very satisfactory owing to the heat conducted away by the aluminium wire. On one occasion, however, the current was sensibly the same in both directions, but rose in the direction *B*, and fell in the other direction. A more satisfactory arrangement was had by melting a piece of tellurium in the open air, on a piece of sheet aluminium hammered into the form of a shallow dish. As the tellurium melted, a small quantity of greenish fumes was given off, after which it remained quiet, "wetting" the aluminium surface. When a platinum wire touched the melted tellurium, and a current was passed through, it was found to be steady and closely the same for both directions. The resistance rose somewhat when the substances were cooled. An aluminium wire touching the solid tellurium now formed a rectifier—the contact with the sheet aluminium serving as a low resistance contact. When the whole was heated the aluminium wire gave good contact, and when the drop of tellurium was lifted by means of it, and replaced, rectification was obtained in the direction opposite to that just preceding.

Experiments in Various Gases.

Contacts, not chemically clean, carrying small currents showed no loss of rectification when placed in various gases. With large currents, certain effects were observed. In nitrogen there was less bright illumination than in air; *e. g.*, with Te and Al or Mg. Oxygen gave brighter illumination than air, and Mg in contact with Te was ignited by a sufficiently heavy current.

A three-way cock in the system of tubes connected with the Gaede pump made filling the apparatus, Fig. 3 (*a*), with gas a simple matter. The system was exhausted to a Crookes vacuum, while the gas in question passed from the generator and purifying tubes, through the three-way cock. The cock was then turned to permit the flow of gas into the system at any rate desired. After removing the apparatus from the pump, the specimens were broken off or filed as previously described.

Hydrogen.

Hydrogen was made by electrolysis of KOH solution in a water voltameter and was dried by being passed through a tube containing glass beads and phosphorus pentoxide. Tellurium showed rectification of one or two hundredths of a volt in the direction *B* with all the metals, except once when Pb showed a small preponderance of current in the direction *A*. Fused silicon showed rectification for *A*, with all the metals. Carbon gave currents nearly the same for the various metals, while galena usually gave the greater current for *B* with Al, and *A* with Fe, although in the latter case the readings were often the same, as was the case with Pb.

Carbon Dioxide.

Carbon dioxide was generated by the action of hydrochloric acid on marble, purified by passing through potassium hydroxide solution, and dried with phosphorus pentoxide. Tellurium gave usually the same current in the two directions with all the metals, there sometimes being a difference in favor of the direction *B* of one or two hundredths of a volt. The difference, before filing, amounted to tenths of a volt. Fused silicon gave rectification in the direction *A* with every metal. Galena gave much the same values of current, with all the metals, there being rectification in the direction *B* for some contacts with Fe. Graphite, also, showed no rectification except a few times for *A* with Al and Fe.

Nitrogen.

Nitrogen was produced by heating a solution of ammonium chloride and sodium nitrite. It was cleaned by passage through chromic acid and potassium hydroxide solutions, and dried with phosphorus pentoxide. Tellurium showed currents in the two directions with Fe at various currents. The same held with Pb. The currents were the same for Al, with an increase in the direction *B* for some positions. Magnesium gave equal currents, and currents greater for *B* or *A*, depending on the position. The pure Si (Bausch and Lomb) gave the same current in both directions, while the potential varied as much as one hundredth of a volt. This held good for Al as well as the other metals. The fused Si, on the other hand, gave definite rectification in the direction *A*, being especially large with Al. Galena against Mg and Fe gave greater current in the direction *A*, Al in the direction *B*, while with Pb, the currents were either equal, or that for *A* was greater. With graphite the currents in the two directions were equal, except for occasional increases for *A* with all four metals.

Oxygen.

The oxygen was prepared by heating equal parts of pure potassium chlorate and manganese dioxide, and was freed from any moisture by passage through phosphorus pentoxide. An escape tube, extending several centimeters into mercury was provided to guard against excessive pressure. Tellurium (previously melted in vacuo) with oxygen gave rectification with Mg and Al as well as in air, after a few reversals. The same held true for Fe and Pb, but to a somewhat less extent. Pure Si gave more or less rectification in the direction *B*, for various values of current, although sometimes the currents were the same. Fused Si rectified in the direction *A* with all metals, and all contacts except once with Fe when both currents were equal. Galena gave rectification in the direction *B*, strongly with Mg and Al, usually with Fe, and more or less with Pb. With graphite, the currents were sometimes in the direction *A* and sometimes equal; Pb gave, occasionally, a greater current in the direction *B*.

Conductivity of Metal Filings in Air.

As a check upon the previous work, a study was made of the conductivity of metal filings in air and in vacuo. Eccles[1] observed that the coherer does not obey Ohm's law, and the writer[2] has found asymmetry with the coherer, although the phenomenon is not so definite nor so easy to obtain as the deviation from Ohm's law. A case of asymmetry with two copper wires[3] has already been mentioned.

In the present experiments, filings of copper, aluminium, and iron, produced and studied in air, were first examined. The deviation from Ohm's law is considerable, Fig. 5 (*a*) and (*b*). Asymmetry was observed with each of these metals, the current being as much as 45 per cent. greater in one direction than in the other. If the current were kept in one direction for some time, the conductivity rose, but fell in the other direction, as could be seen by making occasional reversals. Aluminium did not show this last effect well, and, in fact, needed considerable pressure to have current flow at all.

Apparatus for Producing Metal Filings in Vacuo.

In order to produce and examine, in vacuo, a sufficient quantity of filings, the apparatus shown in Fig. 4 (*a*) was designed. A file fastened by a joint to an iron rod, to increase the inertia, was enclosed in a long glass tube, *T*, with springs to prevent the file breaking through the ends

[1] Eccles, Electrician, 47, pp. 582, 715, 1901.

[2] R. H. Goddard, Phys. Rev., 28, p. 411, 1909.

[3] Shaw and Garret, Phil. Mag., 8, p. 164.

of the tube. To this tube were attached various other tubes: a Crookes tube to test the vacuum, and a tube, T_1, one end of which could be attached by the ground joint, to the Gaede pump, while the other end—joining T—supported the specimen to be filed, shown enlarged, Fig. 4 (*c*).

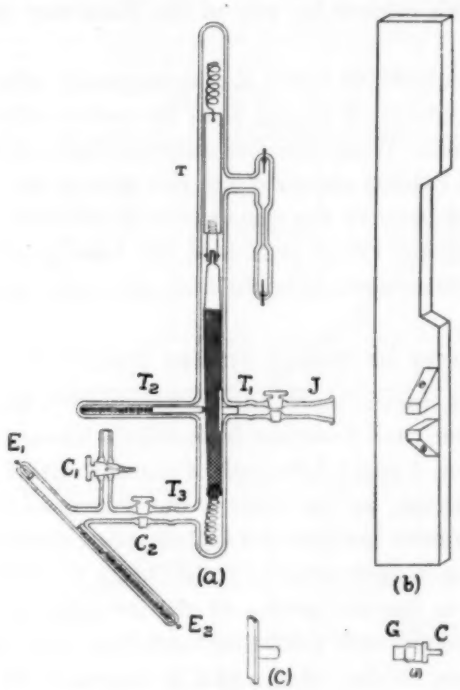

Fig. 4.

In order to press the file against the specimen, an iron rod and a spring were placed in the tube, T_2, the rod being provided at the end with a steel ball, which pressed against the file.

To produce filings, the apparatus was placed on the board, Fig. 4 (*b*) so that T_1 rested in the notch of (*b*), as near the junction with T as possible, and the whole was shaken back and forth. With this method of holding the apparatus there was no shearing stress on the glass, and filings could be obtained almost as rapidly as with a vise in air. In practice, however, the rate was not made excessive, for fear of heating the specimen, and thereby breaking the glass.

When a sufficient quantity of filings had been produced, the tube, T, was turned until the filings dropped through the tube, T_3, into a kind of coherer, in which the conductivity could be tested by means of the electrodes E_1 and E_2. These electrodes were of copper, of a size to fit the glass tube, with platinum foil soldered to the faces to give good

contact. The electrode, E_2, was connected to the platinum leading-in wire with a fine, flexible spiral of copper wire, and could be moved from outside the tube by a magnet. Small quantities of hydrogen and oxygen, produced electrolytically, and dried with phosphorus pentoxide, could be admitted to this coherer by way of the three-way cock, C_1, after C_2 had been closed.

In taking the apparatus apart it was necessary simply to open the upper end of T, and cut off T_1 and T_3 at the points where the letters, T_1, and T_3, are placed. When the file and specimen were introduced or removed, the rod holding the steel ball was pushed out of the way by a stiff wire, inserted between the specimen and the wall of T_1, the end of the wire engaging the crimp that held the ball in place. After each experiment, all filings were removed from the tubes and the surface of the file.

Conductivity of Metal Filings Produced in Vacuo.

With copper, in vacuo, there was no asymmetry, nor change of conductivity with time, nor deviation from Ohm's law as observed in air—there being, in fact, a slight falling-off of current[1] with E.M.F., Fig. 5 (*c*). Occasionally, however, as the voltage was increased in steps of about 1/500 volt, the current jumped to a higher value, thereafter obeying the same law. This is in agreement with the theory of Eccles that deviation from Ohm's law is due to turning of the irregular particles under the influence of the electrostatic field, thus furnishing more contacts at higher voltage. It shows, further, that a film is necessary, to prevent fusions, *i. e.*, good contacts, before this turning can occur. Sparks from a Hertz oscillator several feet away reduced the resistance to a low value.

When oxygen, prepared as above described, was admitted, the resistance increased about 25 times, the deviation from Ohm's law appeared, Fig. 5 (*d*), and asymmetry was observed, there being a tendency for the conductivity in the direction in which the current was flowing to be higher than in the other direction, as in air. When, however, hydrogen was admitted to the copper filings produced in vacuo, there was no noticeable asymmetry, and the current-voltage characteristic, Fig. 5 (*e*), was the same as in vacuo. On removing the hydrogen by opening the cock, C_2, and then admitting oxygen (repeating the operation several times, to remove all the hydrogen) deviation from Ohm's law appeared, Fig. 5 (*f*). In all experiments, the filings were, of necessity, moved about when gases were admitted.

[1] The resistance of the coherer has been found to increase with increasing temperature, owing, probably, to expansion and breaking of some of the contacts. This may account for the deviation in vacuo, if increased heating, due to increasing the current, can produce the same effect.

Aluminium and magnesium did not give results so satisfactory, as a certain amount of pressure was required to give conduction—though much less than that required in air or oxygen. Aluminium filings produced in vacuo, gave deviation from Ohm's law as with copper—Fig. 5

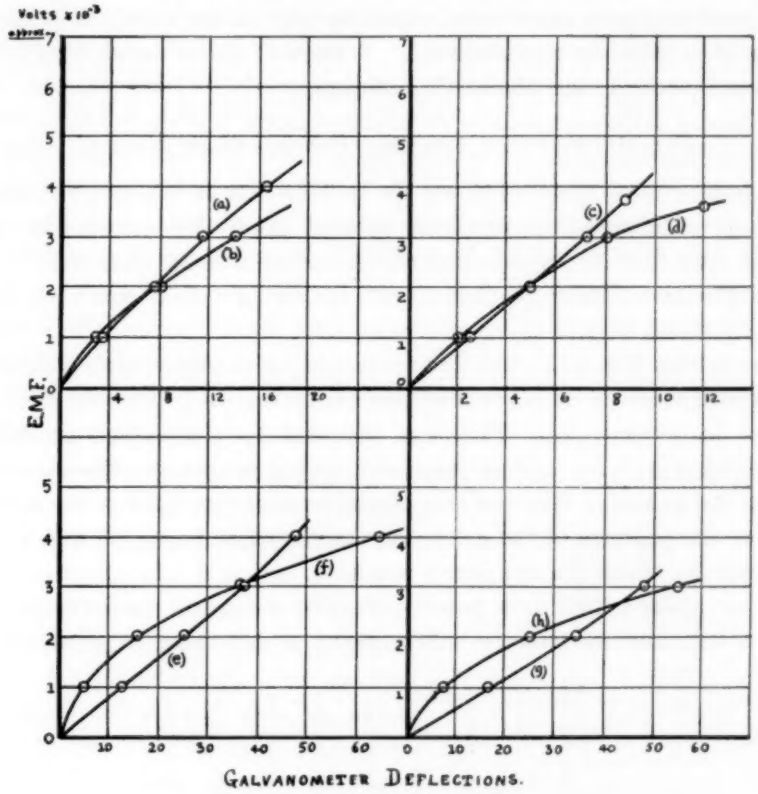

Fig. 5.

(*a*) Copper, in air; (*b*) iron, in air; (*c*) copper, in vacuo; (*d*) copper, in oxygen after vacuum; (*e*) copper, in hydrogen after vacuum; (*f*) copper, in oxygen after hydrogen; (*g*) aluminium, in vacuo; (*h*) aluminium, in vacuo.

(*g*); although occsaionally as (*h*), which, since pressure is necessary for conduction, is easily explained by turning of the particles. No asymmetry was observed. When oxygen was admitted the resistance increased greatly, and the deviation from Ohm's law was large. Hydrogen, acting on filings produced in vacuo, necessitated a little greater pressure for conduction, gave deviation from Ohm's law as in vacuo, and no asymmetry.

It was thought that impurities in the aluminium might necessitate the application of pressure, but it was found that magnesium filings required pressure at all E.M.F.'s, even when no ground joints, *i. e.*, vacuum wax, was used. Magnesium behaved in other respects like aluminium.

ODOR OF ALUMINIUM AND MAGNESIUM FILINGS.

It may be of interest to note, in passing, that the filings of aluminium and magnesium, when produced in vacuo, gave a strong odor somewhat resembling garlic even when the tube was not opened until over a week after performing an experiment; and the odor in the tube still persisted a day or so after air was admitted. A piece of either metal, filed in the air, lost its odor in less than half a minute.

CONDUCTIVITY OF GALENA, POWDERED IN VACUO.

In order to test whether or not the peculiarities of conductivity across contacts of chemical compounds depend upon the surrounding gas, galena was filed in vacuo, and the resulting powder examined. The apparatus was similar to that shown in Fig. 4 (*a*), except that there were no cocks, C_1 and C_2.

The galena, Fig. 4 (*g*), was first set in a block of solder, after which this block was soldered to a piece of copper, turned in a lathe to the form shown in section, (*c*). This was fastened to the holder previously described, Fig. 3 (*b*), and in place of a spring to furnish pressure of the file on the galena, a lead rod was placed in the tube, back of the holder, so that the pressure of the galena on the file could be varied by varying the angle at which the apparatus was held.

In air, galena filed to a powder, showed deviation from Ohm's law, Fig. 6 (*a*), and asymmetry—there being a difference in conductivity

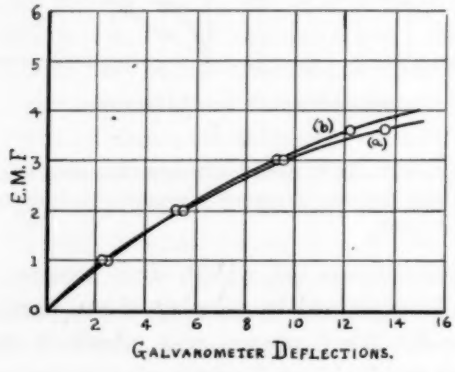

Fig. 6.

Powdered galena. (*a*) In air; (*b*) in vacuo.

of 10 to 15 per cent. for the two directions. The conductivity in the direction of an applied steady current increased faster than that in the opposite direction, observed by reversals, independent of which conductivity was the greater. In vacuo the deviation was still present,

Fig. 6 (*b*), together with asymmetry of the same nature and magnitude as in air.

Oscillograms of Rectifiers at High Frequencies.

The foregoing experiments show that a film of some sort is necessray to produce peculiarities of conduction at contacts, and it remains to determine how such a film acts. The experiments which follow have thrown some light on this question, although not as much as was anticipated. It has already been shown by Pierce[1] that no effect is present for a time longer than 1/6,000 of a second that is not accounted for by the voltage-current characteristics of the rectifier for steady currents. In view of the fact that crystal detectors are being used as receivers of waves of 200,000 or more frequency, and further as Merritt[2] has demonstrated that the silicon detector will act for a wave-length as short as 15 cm., it seemed advisable to obtain oscillograms for frequencies of several hundred thousand, if possible.

Apparatus.

The method will be understood by an examination of Fig. 7. A Poulsen arc was used to produce the high-frequency oscillations, as being the best means of producing a continuous train of undamped oscillations, except by using a high frequency alternator. The arc was on used by Dr. Story[3] in a research on the Poulsen arc. A resistance, P_1, and an inductance, not shown, were in series with the arc. In the high frequency circuit was a variable oil condenser, C, and an inductance consisting of three coils, S, S_1, and S_2, of the same shape and size. These were arranged so that all the current passed through S and a variable carbon resistance, P_2, and then branched, part of the current going through a group of rectifiers in parallel, R_1 and the coil S_1, and the other part, through an equal number of rectifiers, R_2, arranged so as to give rectification in the opposite direction, and thence through the coil S_2. The coils

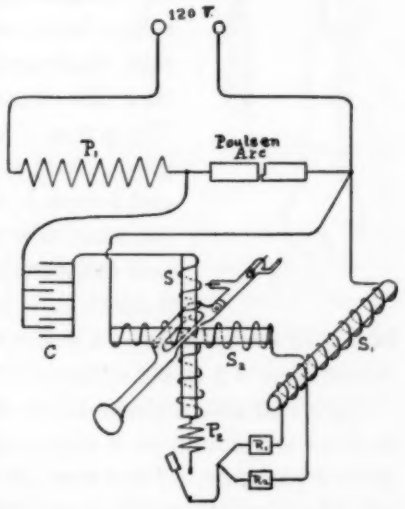

Fig. 7.

[1] G. W. Pierce, Phys. Rev., 28, pp. 153–189, 1909.

[2] Ernest Merritt, Phys. Rev., 32, p. 630.

[3] W. E. Story, Jr., Phys. Rev., 30, pp. 236–261, 1910.

S and S_2 were made to act at right angles to each other, on the beam of cathode rays in a Braun tube, whereas S_1 was a dummy coil. It is easily seen that the total current in the circuit remained the same, for if the rectifiers R_1 hindered the passage of current through S_1, the rectifiers R_2, acting in the opposite direction, would let current through S_2, and vice versa. The rectifiers were made as follows: a large number of pieces of the crystal, to which there was good contact (*e. g.*, by setting the pieces in solder, or clamping them under brass plates) were fastened to a board. A groove was made around the rectifiers, near the edge of the board, and holes were drilled at intervals in the bottom of this groove. Contacts were made by inserting wires in the holes, and bending them until they touched the crystals. After all the wires had been separately adjusted the groove was filled with mercury, thus connecting the wires in parallel.

The Braun tube, made by the writer, was of the special form shown in Fig. 8. The cathode beam was produced by a hole about 1/3 mm. in diameter, in an aluminium disk shown in section, P_1. In this disk was another, larger, hole to facilitate exhaustion of the tube. The rays passing through this second hole were stopped by the aluminium disk P_2. Deflection took place in the tube, t, which was but 2 mm. inside, and 3.3 mm. outside, diameter. A larger tube, T, served to strengthen the apparatus and aid in evacuating the tube. The screen S was made by spreading powdered willemite, mixed with alcohol, on the inside of the bulb and letting it dry—after J. J. Thomson. The part of the main tube below T and t was covered with tin foil and connected, with the anode, to earth. The distance from P_1 to S was 40 cm., and a current of 0.3 ampere in one of the coils gave a deflection of 6 mm. In practice, the current varied from 0.3 to 0.7 ampere.

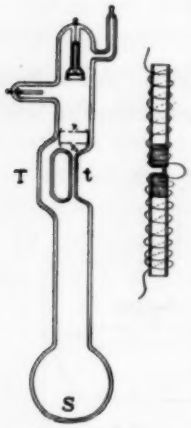

Fig. 8.

Each coil was a single layer of cotton-covered copper wire, 0.5 mm. in diameter, wound on a glass tube, 1.22 cm. in diameter, and soaked in melted paraffine. They were 20 cm. long, with 17 turns to the cm. In order to bring the two halves of these coils as near the tube, t, as possible, they were held in place by the notched plugs of wood, shown in section in the figure.

Instead of using a high potential storage battery, it was found possible to use a Wimshurst electric machine, with or without a condenser in parallel, provided a high resistance formed by a pencil mark on ground glass, was placed in series. With the proper resistance (not easy to get)

the cathode beam was extremely steady, and the glow in the tube persisted for a minute or more after stopping the machine. Lines ruled on paper with india ink[1] were more satisfactory.

Experimental Results.

The oscillogram, a Lissajous' figure, shown in Fig. 9 (*a*),was obtained with silicon against steel, under exceptionally good circumstances. There were 30 contacts in each group, R_1 and R_2, and the calculated frequency was 410,000. The phenomenon could be repeated as many times

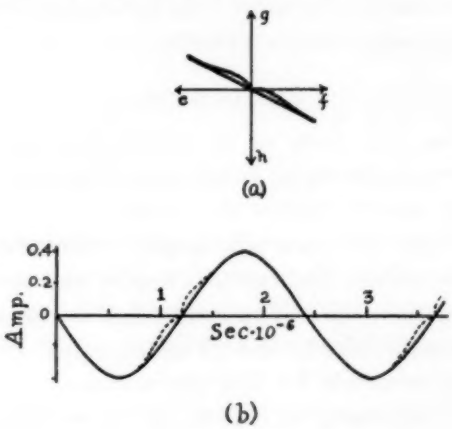

Fig. 9.

f, direction of total current; *g*, direction of greater rectified current; *h*, direction of lesser rectified current. Frequency 410,000.

as desired, but the arc did not remain steady longer than two or three seconds, too short a time, it was found, to affect a photographic plate. The failure of the arc to give oscillations for a longer period was no doubt due to the comparatively large resistance of the groups of rectifiers. At other times these curves were only feebly approached, which was true also, of the same number of contacts with copper, molybdenite and aluminium, tellurium.

The conclusions which are indicated are shown in Fig. 9 (*b*), where the deviation is from a sine wave form instead of the straight line in the Lissajous' figure. There is, apparently, an opposition to the current, or a back E.M.F., which appears for about 4×10^{-7} second, followed by an increase in current lasting the same length of time, when the current is reversed. It strongly suggests a crowding of ions against the film, and the springing-back of these ions at the instant the current is reversed.

[1] F. A. Aust. Phys. Rev., 32, pp. 732–733, 1911.

CRITICISM OF THE EXPERIMENT.

It seems likely that important information could be obtained by using a high-frequency alternator, thus making it possible to obtain photographic exposures of a minute or more. Perhaps, also, more persistent oscillations could be had with the arc by using a great many contacts in parallel, to reduce the resistance. In either case a large number of contacts would be necessary, each adjusted for maximum rectification, and for equality with the other contacts as to current in both directions. If the voltage were considerable, it might be necessary to place several of these groups in series. A smaller hole in the diaphragm, P_1, could be used to advantage, with a long exposure.

CONCLUSIONS.

1. Pure elements give little or no rectification against pure metals, unless oxygen (or an active gas) is present. The evidence in support of this is as follows:

(*a*) Pure tellurium and pure silicon give practically no rectification against metals, in vacuo, hydrogen, nitrogen, and carbon dioxide, but behave in oxygen as in air. The conclusion is also supported by the action of an aluminium wire broken off under melted tellurium. Natural graphite is at best uncertain for slow alternations.

(*b*) A piece of tellurium, melted in air in contact with a piece of aluminium, shows unilateral effects or not, depending upon whether or not the tellurium adheres firmly enough to "wet" the aluminium surface.

(*c*) Copper filings in the form of a coherer, produced and examined in vacuo or hydrogen, show no asymmetry, and deviate from Ohm's law with an upward slope, but in oxygen give the well-known deviation observed with filings produced in air. Aluminium and magnesium do not, however, show such conclusive behavior.

(*d*) Currents of 0.5 ampere or more, in air, give evidence that whatever unilateral effects appear are due to the presence of oxygen, for the following reasons: the direction of greater current, for sufficiently large current, is from metal to substance regardless of the direction for small currents. This is the direction for tellurium for all currents; and this element, by (*a*), rectifies owing to the presence of oxygen. Further, for large currents there appear incrustations, with colors characteristic of the oxides of the substances used. The current in the direction of metal to crystal is the more unsteady, for large currents, as it is with tellurium.

2. Rectification, other than that due to the presence of oxygen, occurs at contacts of impure elements or chemical compounds.

(*a*) Impure, fused, silicon rectifies under all circumstances.

(*b*) The behavior of galena in air and vacuo also lends support to this conclusion, although it is, at best, an uncertain rectifier.

(*c*) Galena, filed to a powder in vacuo, shows deviation from Ohm's law exactly as in air. The deviation is of the same character as that observed previously by the writer for many other powders in air, the effect appearing under all circumstances except when the powders were subjected to great pressure.

(*d*) Chemical compounds, in air, usually rectify in the direction opposite to that with pure elements in air or oxygen.

3. The phenomenon is due, primarily, to the presence or formation of a film at the contact.

(*a*) Pure elements require the presence of oxygen (therefore of oxide) at the contact.

(*b*) The resistance of copper filings produced in vacuo increases 25 times on admission of oxygen. A similar change takes place with aluminium and magnesium filings.

(*c*) In many cases, with large currents, the current remains large, for a second or so, after reversing to the direction of lesser current. This indicates that the building-up of resistance requires a certain amount of time.

(*d*) In the experiment with melted tellurium, with large current, a small E.M.F., after application of a larger E.M.F., both in the direction of greater current, gave practically no current, but gave 0.008 ampere on reversing. This was evidence of a deposit which the small E.M.F. could gradually remove *if applied in the direction of greater current.* Also, since 10 volts gave ½ ampere, while 1 volt gave no readable deflection, there is evidence that the larger current kept flowing either because the heat developed, or the E.M.F., or both, continually broke down the film.

(*e*) The experiment with Fe_3O_4, Si, large current, in which a single spark was visible (microscopically) when the current was passed in the direction of lesser resistance, five minutes *after* the circuit had been broken with the current in the direction of higher resistance, indicates the breaking-down of a resistance at the contact. The continued sparking in the direction of higher resistance, at large currents, with this and other contacts, indicates that the irregularities observed for this direction, *A*, are due to breaking down and sparking. Further, the changes in brightness of the substances and metals, on reversal of current, are indicative of changes in the place of greatest heat production, or changes in heat conductivity, but are not so easy to interpret as the following special experiments.

(*f*) When galena, Fe_3O_4, or silicon were placed between the ends of two aluminium wires, and a current of two amperes passed through, blue sparks appeared and the metal was redder, on the side the current entered the crystal. The entire substance was red hot. In this case a comparatively large region was heated, and if oxygen was deposited, as might be expected, on the anode wire, more heat should be generated, owing to greater resistance, at this surface. Hence the metal should be redder, as was observed. Continued sparking showed continued breaking down of the film—presumably of oxygen with Fe_3O_4 and silicon, and of sulphur with galena.

On the other hand, in the experiment in which a large current was passed through a small contact between two large pieces of silicon, the silicon on the side at which the current passed *from* the contact was redder. The probable explanation is that a *small* region was heated, owing to the very refractory nature of silicon, and that the heat generated in this small region passed more easily to the piece of silicon on which there was no film of oxide, since the thermal conductivity of the film was probably small compared with that of the hot silicon.

(*g*) The experiments mentioned at the beginning of the paper, concerning the change in resistance of rectifiers measured by a very small current, after a current of about 10^{-2} ampere had passed through the contact are indicative of the building up of some sort of permanent resistance, but the data do not show sufficient regularity to enable further conclusions to be drawn.

4. Solid rectifiers are, apparently, analogous to the aluminium valve, or electrolytic rectifier. In this rectifier a solid film is produced and large ions are packed against it, giving a back E.M.F., when the current passes in one direction, whereas smaller, negative, ions pass freely through the film when the current is in the opposite direction. The greatest point of dissimilarity is the continued breaking down of the resisting film, in the case of solid rectifiers, probably due to heating.

(*a*) The hysteresis effect observed by Pierce with carborundum, for the first few reversals, together with the fact, observed by the writer, that tellurium cleaned in vacuo required a few reversals before showing good unilateral effect, when oxygen was admitted, are both analogous to the slow building up of resistance with direct current, for a fresh plate in the aluminium valve, before an alternating current has been applied.

(*b*) The oscillogram at 410,000 frequency suggests the building up of a back E.M.F., which gives a slight additional current at the moment the current is reversed. This conclusion is, however, based upon a single experiment.

SUMMARY.

1. A large number of experiments with currents up to 9 amperes suggested the necessity of using contacts of as nearly chemically clean surfaces as possible.

2. By means of a glass apparatus which could be evacuated to a Crookes vacuum, it was possible to break or file the ends of substances and metals in vacuo, and measure the conductances. Proceeding in this way it was found that tellurium and pure silicon lost most or all of their power to produce rectification when cleaned as above, in vacuo, hydrogen, nitrogen, and carbon dioxide, but behaved in oxygen as in air. Fused silicon and galena gave rectification in vacuo and all gases; the former always, the latter often. Galena and natural graphite were found uncertain even under ordinary conditions.

3. Copper filings produced and examined in vacuo and hydrogen did not show the anomalies of conduction manifested in air and oxygen. Aluminium and magnesium gave uncertain results. Galena powdered in vacuo by filing showed the same anomalies as in air.

4. The experiment with copper filings supports the theory of Eccles, that the deviation from Ohm's law of the coherer is due to turning of the particles, due to electrostatic forces, so that the long axes point in the direction of the current. Although Ohm's law was practically obeyed, there were sudden increase in conductance on raising the voltage. There was little evidence of turning in general, however, unless a film of oxide was present—although Hertz waves greatly increased the conductance.

5. From the experiments mentioned in (2) and (3) it is concluded that rectification is of two kinds, "surface" and "body" rectification, and that the former takes place with pure elements in an active gas, and the latter with impure elements and chemical compounds, irrespective of the nature of the gas present.

6. Many experiments with contacts in air carrying large currents, and contacts in vacuo, showed phenomena which suggested that a film of some sort is necessary in order to have rectification. These experiments, together with an oscillogram of a number of silicon, steel rectifiers in parallel indicate that the action of the solid rectifier is like that of the aluminium valve, or electrolytic rectifier; *i. e.*, a film is formed which hinders the motion of certain ions—with this difference, that, in solid rectifiers the film is broken down by heat, or sparking, so that some current usually flows in the direction of higher resistance.

CLARK UNIVERSITY.

January 10, 1912.

AN ELECTRICAL METHOD OF MEASURING SMALL INTERVALS OF TIME.

BY F. C. BROWN.

WHEN it is desired to measure the time between two mechanical operations, we have found that it may be carried out quite accurately by the use of resistances, battery, ballistic galvanometer, condenser, and contact keys. The principle is based on the relation between the electro-magnetic and the electro-static systems of units, and if we define the ohm in terms of the dimensions of a mercury column, the method is an absolute one. Aside from the advantage of having an absolute measure of time in terms of length, or of length, mass and resistance, the advantages of the method are simplicity and ease of manipulation. The interval of time to be measured may be diminished to the limits of dependable electrical contact, no doubt less than 0.001 second. How large the interval may be varies from 0.4 second to several seconds depending on the period of the galvanometer.

THEORY.

The theory of the method is essentially the same as that given in a previous paper on a method of measuring fluctuating resistances,[1] but as Dr. Erich Schneckenburg, of Berlin, has kindly pointed out that the method of derivation of equation (1) in that paper is not obvious, I shall briefly review the essential steps.

Suppose it is desired to know the interval of time, Δt, between the making of electrical contact at t_1, and the time of breaking of contact at t_2. It is to be shown that this time interval varies directly as the throw of a ballistic galvanometer which has been connected, as shown in Fig. 1, in a Wheatstone's bridge circuit during the interval.

Considering the battery resistance small compared to the other resistances, we obtain, by Kirkchhoff's and Ohm's Laws, the current through the galvanometer to be

$$i = \frac{E(aR - bx)}{(k_1 x + k_2)^2}, \tag{1}$$

where

$$k_1 = Gb + aG + ab + aR + bR,$$

$$k_2 = aRG + bRG + abR.$$

[1] By Brown and Clark, PHYS. REV., XXXIII., p. 53, 1911.

By differentiating equation (1) with regard to x, we have

$$\frac{di}{dx} = -\frac{E(bk_2 + k_1aR)}{(k_1x + k_2)^2}. \tag{2}$$

We may write this equation in the following form and keep within the accuracy of laboratory experimentation,

$$\Delta i = -\frac{E(bk_2 + k_1aR)\cdot\Delta x}{(k_1x + k_2)^2}, \tag{3}$$

where it is understood that if the value of Δx is relatively too large a small correction must be added.

Now if it is agreed that Δx is to be measured as the amount of variation of x from that value which gives no current through the galvanometer as required by equation (1), then obviously $\Delta i = i$, and since the negative sign is of no importance,

$$i = \frac{E(bk_2 + k_1aR)\cdot\Delta x}{(k_1x + k_2)^2}. \tag{4}$$

Since the quantity of electricity that passes through the galvanometer as the result of the closed circuit during the interval Δt is $Q = i\cdot\Delta t$, and since in a ballistic galvanometer $K\cdot d = i\cdot\Delta t$, where K is the usual constant as obtained by a standard condenser and a known electromotive force, it follows that,

$$\Delta t = \frac{K\cdot d\cdot(k_1x + k_2)^2}{\Delta x\cdot E\cdot(bk_2 + k_1aR)}. \tag{5}$$

The only qualification, that should be made to this result is, that either the galvanometer coil must not have moved over an appreciable distance during the time interval to be measured, or that the effective resistances in the closed circuit should be so large that the damping action can be neglected. I take it that it is quite generally understood that self induction in the coil of a ballistic galvanometer can be disregarded. At any rate the experimental results in this paper will obviously warrant the assumption.

If a standard condenser of capacity C is charged by the same electromotive-force E, and then discharged through the same galvanometer, thereby giving a deflection d', we may write equation (5) in the form,

$$\Delta t = \frac{C\cdot d\cdot(k_1x + k_2)^2}{\Delta x\cdot d'\cdot(bk_2 + k_1aR)}. \tag{6}$$

We therefore have the interval of time between the two contacts

measured in terms of the units of length and the units of resistance, and if we choose to define the unit of resistance in terms of the dimensions and the mass of a mercury column, our fundamental system of units may be regarded as solely based on the units of length and of mass. The relative merits of the unit of time as a derived unit will be discussed later.

Experimental Test.

In order that the method may be workable it is sufficient to show that the time interval, between contacts at t_1 and at t_2, varies directly as the deflection of the galvanometer, and that the computed value of the interval agrees with that observed. In our former paper the relation between the deflection and the time was recorded, but the linear relation did not hold for greater values of the time than 0.2 second. The lack of agreement beyond this point has since been found to have arisen from inaccurate theoretical calibration of the timing pendulum, and not to the fact that the galvanometer coil was not in its zero position while the entire quantity of electricity was impressed, as was previously supposed. Using correct values of the time as obtained by an experimental calibration of the pendulum, Messrs. T. Ingwaldson and J. S. Hilliard of our laboratory have obtained the observations shown on the curve in Fig. 2. Each point shown on the curve is the average of four observations. The accompanying table gives a fair representation of the reliability of the observations for a single setting of the keys. However it was found at the close of the observations that there was an error of about one mm. in the throw of the galvanometer due to the inaccurate setting of the keys.

Table I.

Time Interval Between Keys. Seconds.	Throw of Galvanometer. Mm.
0.009	6.0; 5.8; 5.5; 5.7.
0.045	26.5; 26.8; 26.8; 26.8.
0.38	222.0; 222.0; 221.8; 222.4.
0.09	53.0; 53.0; 54.0; 53.5.

The indicated values of the resistances used for balancing the bridge were, $a = b = x = 9{,}000$ ohms, and $R = 9{,}004.6$ ohms. The source of electromotive force was a storage battery of 38.0 volts. The value of R indicates the probable error in the resistances. In order to obtain the observations given above the value of x was changed to 9,100, thereby giving a value of $\Delta x = 100$ ohms. The resistance of the galvanometer was 950 ohms, and its period was 26.7 seconds.

The linear relation between the throw of the galvanometer and the time holds between 0.002 second and 0.32 second as accurately as the

particular apparatus was capable of testing. Of course for longer periods of time there would appear appreciable errors due to the swinging of the galvanometer coil in a closed circuit of high resistance. It is possible to correct for this error or to diminish it greatly by increasing the resistances and by increasing the period of the galvanometer. By increasing the mass of the galvanometer coil without increasing its inductance, *i. e.*, such as is done by adding weights to the coil, will clearly doubly lessen the relative error due to the cause above mentioned. But as adding mass in this way also decreases the sensibility, I am not prepared to say how far the last idea could be carried satisfactorily. To show the adaptability of the method for measuring intervals of time larger than those given in Table I., the period of the galvanometer coil was increased to 91 sec. by using a phosphor bronze strip suspension 1 meter in length.

TABLE II.

Deflections.

1 Period.	Current Direct.	Reversed.	
0.9 second.....	33.6	28.0	
	34.0	26.0	
	32.0 zero at 3.5	27.8	
	34.2	26.0	
	32.8	26.2	av. 30.1
2 periods.....	56.5	65.5	
	57.0	64.5	
	55.8 zero at 5.0	64.1	
	55.0	64.1	
	55.4	66.1	av. 60.5
3 periods.....	94.5	92.3	
	87.2	94.0	
	87.8 zero at 3.0	93.1	
	90.0	92.0	
	86.0	92.5	av. 90.7
4 periods.....	109.2	116.0	
	108.0	118.2	
	110.5 zero at 4.0	117.0	
	110.2	117.5	
	110.5	118.4	av. 113.7
5 periods.....	139.0	131.0	
	139.2	130.1	
	139.2	129.5	
	138.9	129.3	
	138.5	131.2	av. 134.6

The time interval was measured in terms of the number of swings of the pendulum. The keys were knocked down always at the middle of the arc. The period was about 0.9 second and the intervals were therefore some multiple of 0.9 sec. The observations are shown in Table II. The resistances used for balance in the bridge were 9,000 ohms each, and Δx was 500 ohms. A single dry cell was in circuit. When the galvanometer period is so large it is highly advisable to determine the zero position from the amplitude readings to the right and left such as is practiced in balance work. After the zero position is found it is very easy to bring the coil to rest.

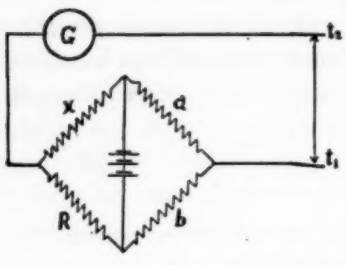

Fig. 1.

It is observed that up to 3 periods, *i. e.*, 2.7 seconds, the deflection is proportional to the time interval, but beyond this the deflection falls off quite rapidly.

However by replacing the 9,000 ohm resistances in a and b (see Fig. 1) with 100,000 ohm values each, the deflection was proportional to the time up to about 3.6 seconds as shown in the following table, where each recorded value is the average of ten observations.

TABLE III.

2 periods	55.0
4 periods	110.7
5 periods	132.6

The foregoing results would seem to indicate that for large intervals of time it is more important to have a long period than it is to have extremely high resistances.

In order to test the adaptability of the method for absolute determinations of time, the constant of the galvanometer as obtained by equation (5) was compared with the value as obtained by the well-known battery and condenser method. By the current method the value was calculated to be $K = 1.77 \times 10^{-10}$ coulombs per mm. and by the second method, $K = 1.82 \times 10^{-10}$. This variation is quite within the limits of error of the capacity and the resistances used. As we did not have a standard condenser or resistances of the highest accuracy, it was not considered worth while to investigate the possible accuracy of the method any further.

As a practical laboratory method of measuring small intervals of time I believe that the scheme presented should be useful in certain kinds of

work, wherever it is feasible to mark time by electrical contacts. We believe that it is advisable to reserve in every laboratory a ballistic galvanometer of very slow period primarily for measuring time intervals. By posting at this galvanometer particular values of resistance and of

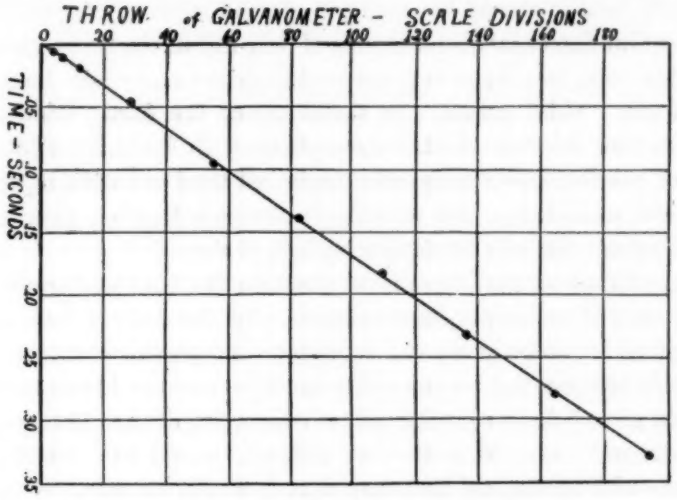

Fig. 2.

electromotive force to be used, and also the equivalent time interval, as calculated, for one division deflection, the troubles of calculations can be eliminated once for all. By taking only the most elementary precautions therefore the method should in many cases supplant a chronograph and standard clock. From this point of view the simplicity and quickness of manipulation are striking.

If it is desired to measure two or more time intervals simultaneously, several galvanometers and sets of keys may be connected in the same bridge circuit. The use of two galvanometers is illustrated, as used for measuring fluctuating resistances, in my previous paper on the recovery of the Giltay selenium cell and the nature of light-action in selenium.[1] If one observer wishes to read several time intervals simultaneously, he can do so by altering the periods of the galvanometers sufficiently so that he can have time to record each deflection.

The Advisability of the Second as a Derived Unit.

Quite apart from the usefulness in the laboratory, are the considerations concerning the practicability of the method for determining the absolute unit of time. In this discussion any of the well-known methods used

[1] Phys. Rev., XXXIII., p. 412, 1911.

by standard laboratories might be substituted. The only question is whether it is best to have the second as a fundamental or a derived unit of time. A fundamental absolute unit should have two distinct merits. It should be one capable of being reproduced to a sufficiently high degree of accuracy, and it should be unvarying for all time. As is well known our present fundamental absolute unit of time fulfills the first requirement remarkably well, but there is considerable doubt as to how long it will remain fixed. Tidal action, the shrinkage of the earth, friction with meteorites and friction of the atmosphere with itself, in addition to friction of possible electromagnetic origin, all tend not only to vary the value of the second, but also to make it almost a hopeless task to satisfactorily correct the unit for future periods of time.

By way of comparison, there is no question but that we cannot reproduce the unit of resistance, and consequently the derived unit of time, with as great accuracy as we can reproduce the present absolute fundamental unit of time, but on the other hand we have no information that would lead us to believe that the unit of resistance, defined in terms of the dimensions and mass of a mercury column, would not remain fixed.

It seems wise to suggest therefore that it would be worth considering the advisability of adopting our present unit as a secondary standard, which might be rechecked and revised in the distant future, if the electrical method, with the ohm as the fundamental unit, should show the value of the second to be materially in error. At any rate the temporary establishment of the unit of time defined from as many sources as possible might lead to discoveries of far-reaching importance.

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PHOTO-ELECTRIC POTENTIALS OF THIN CATHODE FILMS.

By Paul H. Dike.

THE velocity with which electrons are emitted from a metal plate in a vacuum when illuminated with ultra-violet light has been investigated by several observers, beginning with Lenard, and has been studied with increasing activity in recent years. In the earlier investigations the velocities of the electrons were measured usually only as a subsidiary problem to the study of the current maintained by the stream of electrons given off. More recently, however, much work has been done on the study of the conditions affecting the initial velocities of the electrons.

Two general methods of procedure are open for the measurement of the electronic velocities. The minimum positive potential to which a plate must be raised to prevent the escape of the fastest electrons projected from its surface may be measured directly by allowing the plate to charge itself up to a maximum potential under the action of light, all other conductors in the neighborhood being earthed, or it may be determined indirectly by measuring the current produced, on exposure to the light, between the surface and a charged conductor placed near it, as a function of the difference in potential maintained artificially between the two conductors. By varying the potential on the second conductor a value is found for which the current becomes zero, the negative potential on the second conductor then being just capable of preventing the escape of any electrons from the surface.

For various reasons the results obtained by different observers for the value of the photo-electric potential are not very accordant, though they have one common feature, namely, the observed potentials are in general low. The stream of electrons projected from a metallic plate by the action of ultra-violet light may be considered as an aggregation of slow-moving cathode rays, and it has been shown only recently by von Baeyer and Gehrts that like other cathode rays they are subject to reflection and can produce secondary radiation on striking a surface, though they do this to a less degree than ordinary cathode rays and have a range of only a few centimeters. Hence, as might be expected, the size and shape of tube and the arrangement of the electrodes have been found to in-

fluence very strongly the results obtained. It is well known that the potentials may also be affected by the atmosphere and pressure in which the test was conducted, the wave-length of the light used, and the condition of the surface, but the potential has been found to be independent of the intensity of the incident light.

Some representative values are given below:

Observer.	Surface.	Max. Pot. Volts.	Remarks.
Ladenburg[1]	Platinum.	1.86	Electronic reflection neglected.
Ladenburg[1]	Copper.	1.69	Electronic reflection neglected.
Ladenburg[1]	Zinc.	1.12	Electronic reflection neglected.
Ladenburg and Markau[2]	Platinum.	2.3	Electronic reflection reduced.
	Lampblack.	3.5	Electronic reflection reduced.
Hull[3]	Lampblack.	3.5	Electronic reflection reduced.
Klages[4]	Mercury.	2.3	Electronic reflection reduced.
Von Baeyer and Gehrts[5]	Gold, copper and aluminum.	6.3	Electronic reflection reduced.
Millikan[6]	Copper.	20	Tube not described.
	Aluminum.	12.5	

The observations reported by Millikan were carried out with plates which were kept for months in very high vacua with frequent prolonged exposure to intense ultra-violet light, giving unprecedentedly high potentials for iron, zinc, copper, silver and aluminum, in all cases many times higher than when the plate was first put in the tube. He apparently supposes that the light in some way cleans the surface, possibly by removing a gas layer, though such a result is quite the contrary of what would be expected from the usual behavior of a metal when so exposed to the light, a fatigue effect being in general observed.

It was with the hope of producing some similar effect by other means that the work to be described was undertaken. If the metal surface could be cleaned in vacuum, so as to free it from surface layers, or if it could be produced in vacuum and tested without exposure to any outside gases it seemed possible that the desired result might be achieved. The most feasible way of cleaning the plate appeared to be by means of the cathode discharge, using the plate to be cleaned as cathode, subjecting it

[1] Verh. der Deutsch. Gesell., 1907, p. 504.
[2] Verh. der Deutsch. Gesell., 1908, p. 562.
[3] Am. Jour. of Science, XXVIII., Sept., 1909, p. 251.
[4] Ann. der Phys., 31, 1910, p. 343.
[5] Ber. der Deutsch. Phys. Gesell., 21, 1910.
[6] PHYS. REV., XXX., Feb., 1910, p. 287.

to the bombardment of the canal rays and tearing off the particles which make up the cathode deposit. It has since been learned that this was a part of the process used by Millikan and by von Baeher and Gehrts in preparing the plates which gave the high potentials, as well as by several other observers, notably Christler,[1] studying the photo-electric current rather than the potential.

Numerous tests were made of this method of preparing the surface, in two tubes of different types, in atmospheres of hydrogen and of nitrogen at very low vacua, using copper and iron as the metals to be tested. The results obtained showed that the potential to which either of these metals could be raised by the action of ultra-violet light from the quartz-mercury arc could be only slightly increased by prolonged use as cathode. The highest value observed for the photo-electric potential of copper was 4.0 volts, and for that of iron 3.1 volts. Copper polished with rouge gave a potential of 3.8 volts before being used as cathode.

As this line of attack did not yield the high potentials looked for, another process was tried, using the plate to be tested as a receptacle for a cathode deposit, and examining its photo-electric properties under various conditions and with varying thickness.

One end of a brass tube (Fig. 1) was closed with a piece of plate glass, *C*, into which the electrode leading to the electrometer was sealed by means of a hard cement, the inside of the plate being protected from the discharge by means of a brass shield, *D*, fitting loosely inside the tube. The tube was provided with two side tubes, one for admitting the light to the plate, *A*, and the other for an observation window, not shown in the figure, to permit watching the surface of the plate under test. A glass plate with a good optical surface formed the receptacle for the film, a connection being made from the front of the plate to the metal of the electrode by means of a bit of gold leaf, so placed as to be out of the path of the light. This plate was placed about three centimeters from an iron plate which was used as cathode and kept at a negative potential, while the glass plate and the walls of the tube were earthed in order to prevent "soak" of the charge into the insulation of the electrode. An initial test

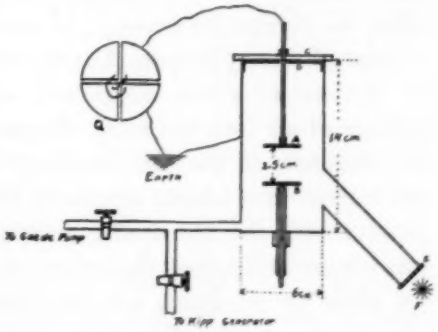

Fig. 1.

[1] PHYS. REV., XXVII., 1908, p. 267.

of the glass plate before any discharge had been passed through the tube showed that it was photo-electrically inactive. After depositing for 90 minutes in an atmosphere of nitrogen using a current of from 2 to 5 milamperes from the 2,000 volt generator set, a test was made giving a potential of 3 volts. A second deposition, lasting one hour, gave 1.2 volts, and continued deposition, aggregating about four and one half hours in all, gave no increase in potential, the thinnest film giving the highest potential obtained. The film on removal from the tube was found to be very irregular in thickness and crossed by several interference bands, so that no good estimate of the thickness for any particular observation could be made.

As iron deposits with some difficulty and is liable to oxidation if the gas in the tube is not entirely free from oxygen, a cathode of sheet platinum was substituted for the iron in the next series of observations, so as to deposit a platinum film on the glass plate, the tube still containing an atmosphere of nitrogen. The glass plate gave no deflection of the electrometer when exposed to light from the mercury arc before deposition. During deposition of a film tests were made of the photo-electric potential at intervals of from one to ten minutes of actual time of discharge. During discharge the current was maintained as constant as possible by regulating the pressure in the tube. This was accomplished by admitting more nitrogen when the current decreased and connecting to the pump when the current increased. It was attempted to maintain an average current of 0.0025 ampere, but the fluctuations from the mean were large. At the end of a run, which was usually terminated by an accidental leakage of air into the tube, the plate was removed from the tube and the thickness of the film measured. This was done by making use of the interference fringes produced by placing a piece of optical glass in contact with the film under sodium light. A narrow strip of the film was scraped off across the center of the place and the fringe-shift from the glass to platinum was measured under a low power micrometer microscope, as a fraction of the distance between two successive fringes, which gives the thickness of the film in terms of the wave length of sodium light. To eliminate the possible difference of phase change on reflection from glass and from platinum the plate was replaced in the tube and a second layer of platinum deposited on the first and on the glass surface laid bare by scraping, giving two platinum surfaces from which to reflect. The fringe shift was again measured and found to be the same as before, within the limits of accuracy of the measurements, from which it was concluded that at least for these thin films the difference of phase change in reflection from glass and from metal is negligible.

In order to form an estimate of the thickness of the film at any time during its deposition it is necessary to make the assumption that the thickness of the film is proportional to the time of deposit, which can only be approximately true since it was impossible to keep the current absolutely constant, but no other way is known of determining the thickness of the extremely thin films in which we are here principally interested. The rate of loss of weight of the cathode due to discharge, and hence probably the rate of deposit of cathode film has been found by Granquist[1] to increase rapidly with decrease of pressure, to be proportional to the cathode fall but not to the total potential difference between cathode and walls and at constant pressure to be nearly proportional to the square of the current, while Holburn and Austin[2] find the rate of loss to be nearly proportional to the first power of the current. Since the pressure in the tube as well as the current was kept nearly constant the above assumption seems fairly well justified, though there is room for considerable error. Upon dividing the total thickness of film by the number of minutes of actual discharge we find the average rate of deposit per minute and from this we can determine the probable thickness at any time.

Three films were thus deposited and tested, the results being shown graphically in Figs. 3, 4 and 5, where ordinates represent photo-electric

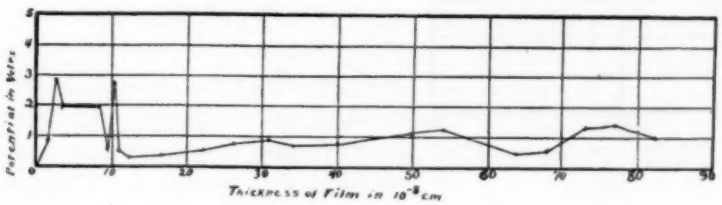

Fig. 3.

potentials in volts and abscissæ-thickness of film in 10^{-8} cm. It will be noticed that while the maximum potentials attained are very different for the three films, they occur at practically the same thickness of film in all cases, namely, 5×10^{-8} cm., and that the sudden drop to a minimum behaves in the same manner within the limits of error in estimation of thickness. This latter thickness, about 10^{-7} cm. is the same thickness of platinum film for which Patterson[3] found a rapid increase in electrical conductivity, the specific conductivity being very low for films thinner than this. This enormously increased photo-electric potential of very

[1] G. Grunquist, Öfvers. k. Vet.-Akad. Förh. Stockholm, 54, pp. 575–594, 1897.

[2] Wiss. Abh. physik. Reichsanstalt., 4, 1904 (99–114).

[3] Phil. Mag., Vol. 4, Dec., 1902, p. 652.

thin films was accompanied by a large photo-electric current as shown by the rapid charging of the electrometer system when the light was turned on, but both effects fatigued quite rapidly with continued illumination and did not recover on standing, that is, the electrometer was deflected quite rapidly to a maximum and then gradually fell back. The thicker films giving lower potentials also gave smaller currents, but did not fatigue appreciably. There is apparently a critical thickness for platinum as deposited on glass beyond which it becomes less easy for the electrons to escape and more easy for them to migrate through the metal as shown by the increased conductivity.

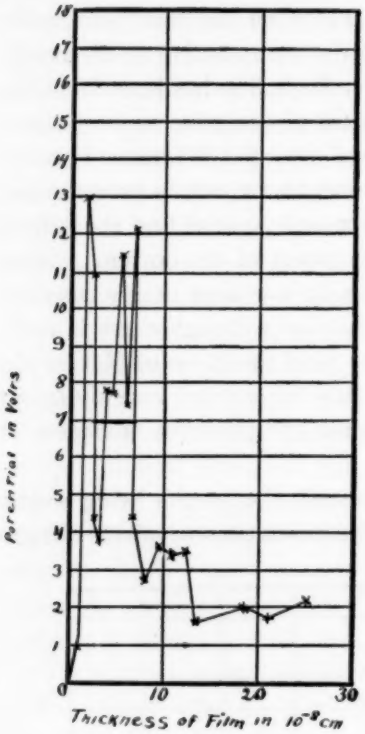

Fig. 4.

The idea suggested itself that the high potentials might be due to the material on which the platinum was deposited, and to test this a quartz plate was substituted for the glass. This was also inactive before being deposited on, but a one-minute discharge sent the potential up to 18 volts and three minutes more sent it beyond to the limit of the electrometer scale, which corresponded to 30 volts. Depositing was continued, for a total of one hour, testing at intervals of one to two minutes of dis charge, and high potentials were obtained throughout, averaging about 25 volts but sometimes going beyond 30 volts and no minimum reached. On removing the plate from the tube a partial explanation of the peculiarities of this film was found in its irregular thickness as shown by the colors of the surface, which resembled interference bands. This was due, partially at least, to the fact that the plate was larger than the cathode, causing the deposit to be less dense toward the edges, and films of all thicknesses were present at the same time. There was reason also to doubt the purity of the gas during this test.

The type of tube so far used was not entirely satisfactory, since it did not allow sufficient flexibility of arrangement of the plates, and the cathode when close enough to the plate to give a good deposit was partly in the path both of the direct and of the reflected ultra-violet light, and moreover formed a good reflector for the electrons projected from the

plate, thus lowering the potentials obtained. A new tube (Fig. 2) was designed to avoid most of these difficulties, in which the cathode (*B*) could be rotated out of the way when not in use by means of a ground

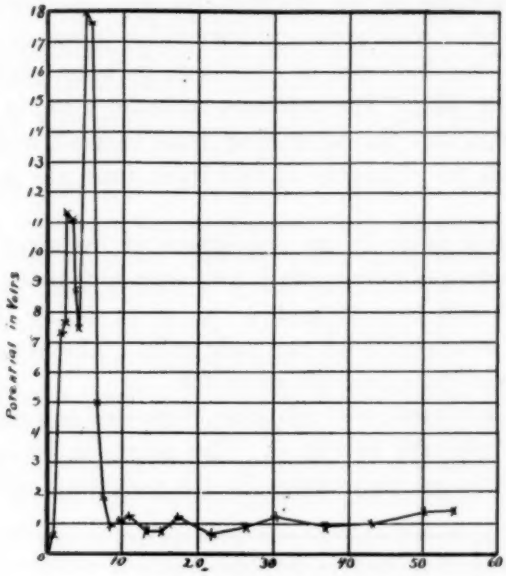

Fig. 5.

joint (*C*). This consists of a brass cone fitted to a conical hole in a heavy plate-glass end (*D*) of the tube. The tube itself was of brass as before, but much larger in diameter. The plate to be tested (*A*) was held in a light frame supported by a yoke (*F*) in such a way that it could be rotated about a vertical axis from outside the tube so as to present either face to the cathode discharge and to the ultra-violet illumination. The light entered the tube through a well-diaphragmed side tube and the beam of light was restricted to the central portion of the plate, which it struck at an angle of 45 degrees when the plate was set so as to be parallel to the cathode. Two other side tubes were provided, so placed that the light *transmitted* through the plate would pass out through one, and the light *reflected* from the plate through the other. All three

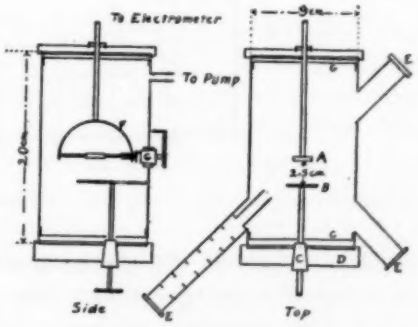

Fig. 2.

tubes were provided with quartz or fluorite windows (*EEE*). This was done in order to avoid as far as possible scattered light inside the tube, as well as to provide a convenient means of watching the plate during deposit. The electrode leading to the electrometer was insulated as before by passing it through a plate-glass end into which it was cemented. Both glass ends were shielded from the discharge by brass plates (*CC*) fitting loosely inside the tube. The platinum cathode, 3 cm. in diameter, was backed with mica and the supporting stem covered with a glass tube in order that all the discharge should leave from the front surface of the cathode.

Deposition took place in an atmosphere of hydrogen, and tests of photo-electric potential were made in a vacuum such that a spark from an induction coil would pass through 4 cm. of air rather than through a discharge tube connected with the main tube. The source of potential for deposition was the 2,000-volt generator.

The first test was made with platinum deposited on quartz, the results being shown graphically in Fig. 6. The points to be noted in regard to it are the continued high values for the potential, and the drop and

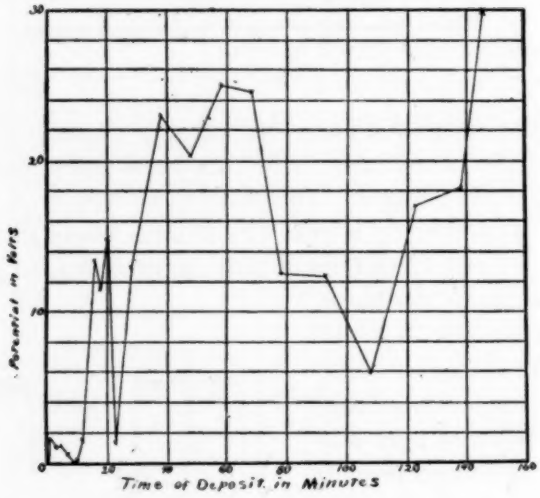

Fig. 6.

recovery after about two hours deposition. The drop coincided with the appearance of a nearly uniform blue coloration of the film. The colors changed with increasing thickness of film from blue to green, to red, and then to blue again, suggesting interference, but the total thickness of the film at the end of the series of tests did not much exceed a half wave-length of sodium light. With the appearance of the blue coloration a

new phenomenon was observed, an ageing effect. If the film was tested immediately after the discharge allowing only sufficient time for the vacuum to be reduced to its usual value during tests, practically no deflection of the electrometer would be obtained, but it if were allowed to stand without exposure to light for an hour or more a potential of two or three volts would be obtained on exposure to the light, and this would increase gradually with time of standing still, after 24 hours or more, the maximum of about 20 volts was attained. This increase took place even if hydrogen or air were allowed to enter the tube, in one case air being admitted up to atmospheric pressure without affecting the potential obtainable on re-exhaustion. The apparent drop in potential at the appearance of the blue coloration is probably due to a failure to allow time for the ageing to take place, since the effect of standing was not discovered till after the low readings had been recorded.

There was a very marked difference in the potentials obtainable from the same film according as the cathode was in position for discharge or not. With cathode up, that is, in position for discharge, the potential would be about 30 per cent. less than when the cathode was turned out of the way, as would be expected from the work of van Baeyer and Gehrts, since the reflection of the electrons was very greatly reduced in the second position.

The film in which the ageing effect was first noticed when removed from the tube appeared colored but fairly uniform with some dark spots. Upon examination under a high power microscope these spots were seen to be thin parts of the film, very small and surrounded with a peculiar radiate structure, so that even in this thick deposit there were thin parts, which may have been responsible for the continued high potentials.

Since a platinum film so thick as to be nearly opaque gave results so different from ordinary platinum, it was of interest to try a film deposited on sheet platinum instead of on glass or quartz. A quartz plate was used as a support for a piece of platinum foil which had been used in an electric furnace at high temperatures for a considerable length of time, the foil being attached to the quartz by means of sealing wax. The foil had a burnished surface and was not polished, but was thoroughly cleaned with French chalk and distilled water.

The results of the observations are shown in Fig. 7, where ordinates represent maximum potentials for a given film, and abscissæ represent times of discharge in minutes. The potentials above 30 volts were measured by means of a gold-leaf electrometer, reading to the nearest volt. These high potential readings could be repeated indefinitely and on successive days, until an addition was made to the thickness of the film.

The same ageing phenomenon occurred here as with the thick film of quartz. The film also showed coloration, and the disappearance of the color was taken as an indication that the film had been removed when the plate was used as cathode to clean it. The films on platinum are seen to combine properties of those on glass and on quartz. They

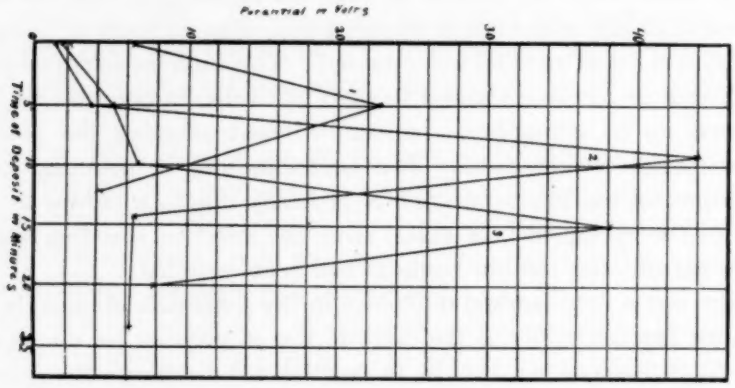

Fig. 7.

resemble those on glass in attaining a high maximum for a certain thickness of film, and at about the same thickness for both glass and platinum, while, like the films on quartz, they show the ageing effect to a very marked degree. The *initial potential* with the platinum foil, *i. e.*, before any film had been deposited, is of the same order as the potentials obtained by von Baeyer and Gehrts for gold, copper and aluminum with elaborate precautions as to vacuum, cleaning of the surface and avoidance of electronic reflection, while here the latter was the only point particularly considered. The high potentials recorded in Fig. 7 exceed any previously reported even by Millikan.

No explanation of these high potentials is obvious and that they are caused by anything else than the true photo-electric effect is hard to believe, since it would seem that the experimental conditions had been sufficiently varied to have disclosed any spurious effect. The potentials were obtained only when the light was on though the sensitiveness to light persisted in some cases for days. There were no insulated surfaces exposed to the discharge which could influence the electrometer, and in the last form of apparatus scattered light was reduced to a minimum. Any errors introduced, such as faulty vacuum, leakage of the electrometer system, electronic reflection, etc., would tend to reduce the potentials rather than increase them.

The films on glass which gave pronounced maxima for a thickness of

about 5×10^{-8} cm., falling abruptly with the increase of thickness to a low value, were colorless and had good mirror surfaces which showed no structure when examined with a high power microscope, while the films on quartz were colored, showed a lack of uniformity and had surfaces not at all like those of ordinary platinum. These colored films gave high potentials no matter how much the thickness was increased, at least up to $\frac{1}{2}\lambda$ for sodium light and in this respect also were different from ordinary platinum.

Hence it may be said that ordinary platinum gives unusually high values for the photo-electric potential only when in an excessively thin film of about 5×10^{-8} cm. thickness, which is of the order of magnitude of the accepted values for the diameters of gaseous molecules; while if it comes down in the form which gives colored films the potentials may be continuously high with increasing thickness of film. The cause of the coloration of the films deserves a special investigation, for interference does not seem to be an adequate explanation.

Ordinary platinum even after it has been rolled probably has some crystalline structure, which becomes more pronounced with long heating and annealing,[1] while our very thin films and the colored deposits probably lack such regular structure and may be considered amorphous. In the amorphous form the molecular bonds are free and may be points of readiest escape for the electrons which are shot off, or the electrons may resonate more freely to the vibrations of the ultra-violet light when the bonds are unsatisfied, acquiring a greater velocity. When the film becomes thick enough the molecular bonds unite to form elementary crystals, and the freedom of the electrons is diminished. When deposited on platinum the film goes down on a surface already crystallized and the molecules deposited do not readily join the old crystals but when in sufficient numbers unite to form new crystals group. The ageing effect, that is, the increase of electronic velocity with time in the case of the films deposited on platinum and on quartz, remains to be explained.

Summary of Results.

1. It has been demonstrated that photo-electric potentials of a platinum surface can reach values more than twice as high as any hitherto reported, and many times higher than any previously obtained with the same source of illumination, namely, the quartz mercury arc.

2. These high potentials were observed only with very thin cathode films of the order of thickness of 5×10^{-8} cm., or with colored films of greater thickness, up to at least a half wave-length of sodium light.

[1] Holborn and Austin, loc. cit.

3. A sudden drop in potential (considered as a function of thickness of film) occurs with uncolored films at the same thickness at which Patterson found a rapid increase in the electrical conductivity of platinum films.

4. With colored films on quartz, and films on platinum the velocity of the projected electrons was found to increase with lapse of time, up to about 36 hours, independent of illumination and state of vacuum.

In conclusion I wish to acknowledge my indebtedness to Professor Mendenhall for his encouragement and numerous suggestions during the course of the work.

Dept. of Physics, University of Wisconsin,
June, 1911.

PROCEEDINGS

OF THE

AMERICAN PHYSICAL SOCIETY.

THE CALCULATION OF THE MAXIMUM VALUE OF THE FORCE BETWEEN TWO COAXIAL CIRCULAR CURRENTS.[1]

BY FREDERICK W. GROVER.

THE force between two parallel coaxial circular currents was given by Maxwell[2] in the form

$$f = \frac{\partial M}{\partial z} = -\pi \frac{z \sin \gamma}{\sqrt{Aa}} \{2F - (1 + \sec^2 \gamma) E\}, \qquad (1)$$

where A and a are the radii of the two circles, z the distance between their planes, and F and E are the complete elliptic integrals of the first and second kind respectively, to the modulus

$$k = \sin \gamma = \frac{2\sqrt{Aa}}{\sqrt{(A + a)^2 + z^2}}.$$

Only for circles of equal radii is the force a maximum when the circles are in the same plane. When the radii are unequal, the force at first increases with the distance z, reaches a maximum, and then falls off indefinitely towards zero as the distance is indefinitely increased.

The maximum value of the force is a function, not of the actual values of the radii, but of their *ratio*, a fact which is taken advantage of in the Rayleigh current balance, the movable coil being placed at such a distance from the fixed coils, that the observed force is a maximum. The calculation of the maximum value of the force as a function of the ratio of the radii possesses therefore a practical as well as a theoretical interest.

The maximum force may be obtained with all the accuracy necessary by calculating the value of the force for various arbitrarily selected values of z in the neighborhood of the approximate value indicated by experiment, the maximum value of the force, and the distance z corresponding, being then derived by interpolation. For the purpose of these calculations, formula (1) may be employed, or some one of the expansions in q functions given by Naga-

[1] Abstract of a paper presented at the Cambridge meeting of the Physical Society, April 27, 1912.

[2] Elect. and Mag., II., § 701.

oka.[1] Of these may be cited the following, which have been extended by the author of the present paper to include several extra terms.

$$f = \frac{192\pi^2 z}{\sqrt{Aa}} q^5(1 + 20q^2 + 225q^4 + 1{,}840q^6 + 12{,}120q^8 + 68{,}052q^{10} + 337{,}465q^{12} + 1{,}513{,}740q^{14} + 6{,}247{,}665q^{16} + \cdots) \quad (2)$$

and

$$f = \frac{\pi z}{16q_1\sqrt{Aa}}[(1 + 12q_1 - 192q_1^3 + 1{,}232q_1^3 - 5{,}634q_1^4 + 21{,}648q_1^5 - 73{,}600q_1^6 + 226{,}944q_1^7 - 648{,}189q_1^8 + \cdots) - 12q_1 \log \frac{1}{q_1}(1 - 10q_1 + 60q_1^2 - 300q_1^3 - 1{,}300q_1^4 - 4{,}884q_1^5 + 16{,}320q_1^6 - 49{,}920q_1^7 + 142{,}500q_1^8)], \quad (3)$$

where

$$q = \frac{l}{2} + 2\left(\frac{l}{2}\right)^5 + 15\left(\frac{l}{2}\right)^9 + \cdots,$$

$$\frac{l}{2} = \frac{1}{2}\frac{1 - \sqrt{k'}}{1 + \sqrt{k'}} = \frac{k^2}{2(1 + k')(1 + \sqrt{k'})^2},$$

$$k^2 = \frac{2\sqrt{Aa}}{\sqrt{(A + a)^2 + z^2}}, \qquad k'^2 = 1 - k^2 = \frac{\sqrt{(A - a)^2 + z^2}}{\sqrt{(A + a)^2 + z^2}},$$

$$q_1 = \frac{l_1}{2} + 2\left(\frac{l_1}{2}\right)^5 + 15\left(\frac{l_1}{2}\right)^9 + \cdots,$$

$$\frac{l_1}{2} = \frac{1}{2}\frac{1 - \sqrt{k}}{1 + \sqrt{k}} = \frac{k'^2}{2(1 + k)(1 + \sqrt{k})^2}.$$

These formulas are in general very convergent, so that only two or three terms need be calculated. Formula (3) applies to the case of circles close together, where (2) is not sufficiently convergent. Tables recently published by Nagaoka[2] facilitate materially the use of these formulas.

As the above method of calculating the maximum force is indirect, the author was led to attempt the derivation of formulas which should reach the result more directly. Although the formulas given below do not materially simplify the calculation, they possess, apart from their academic interest, value in the means provided for rapidly checking the constants obtained by the indirect method.

The expression of Maxwell was first differentiated, and an expression involving z in terms of elliptic integrals derived. This expression seems, however, to be too complicated to admit of practical use. By following the

[1] Phil. Mag., 1903.

[2] Proc. Math. Phys. Soc. Tokyo, 6, p. 152; 1911.

method of Nagaoka, however, and expressing the results in q series, the two formulas given below were derived.

Nagaoka gives the force in the form

$$f = \frac{\partial M}{\partial z} = 4\pi Aaz \int_0^\pi \frac{\cos\theta d\theta}{(A^2 + a^2 + z^2 - 2Aa\cos\theta)^{\frac{3}{2}}}.$$

Differentiating this equation with respect to z we have the condition to be fulfilled by the distance z_0 corresponding to the maximum force

$$\frac{df}{dz} = 4\pi aA \int_0^\pi \frac{\cos\theta d\theta}{(A^2 + a^2 + z_0^2 - 2Aa\cos\theta)^{\frac{3}{2}}} + 4\pi aAz_0^2 \int_0^\pi \frac{3\cos\theta d\theta}{(A^2 + a^2 + z_0^2 - 2Aa\cos\theta)^{\frac{5}{2}}} = 0.$$

The integration of this equation was obtained by introducing the $\mathfrak{p}$ functions of Weierstrass. The result may then be expressed by means of the θ functions of Jacobi, and finally expanded in q series. As the work is long and tedious, only the final formulas can be here given.

$$z_0 = \sqrt{\frac{Aa}{20q}}\,(1 - 18q^2 + 199q^4 - 2{,}022q^6 + 21{,}547q^8 - 242{,}522q^{10} + 2{,}829{,}828q^{12} - 33{,}755{,}570q^{14} + 408{,}424{,}637q^{16} - \cdots) \tag{4}$$

and

$$\begin{aligned} z_0^2[&(1 - 16q_1 + 376q_1^2 - 4{,}672q_1^3 + 38{,}948q_1^4 - 252{,}192q_1^5 \\ &+ 1{,}365{,}888q_1^6 - 6{,}463{,}360q_1^7 + 27{,}500{,}946q_1^8 - \cdots) \\ &- 120q_1^2 \log\frac{1}{q_1}\,(1 - 16q_1 + 154q_1^2 - 1{,}120q_1^3 + 6{,}880q_1^4 \\ &- 34{,}272q_1^5 + 156{,}268q_1^6 - \cdots)] \\ = 32Aaq_1[&(1 + 24q_1 + 36q_1^2 + 384q_1^3 + 402q_1^4 + 3{,}456q_1^5 + 3{,}064q_1^6 \\ &+ 23{,}040q_1^7 + 18{,}351q_1^8 + \cdots) \\ &- 12q_1 \log\frac{1}{q_1}\,(1 + 2q_1 + 24q_1^2 + 28q_1^3 + 264q_1^4 + 252q_1^5 \\ &+ 2{,}016q_1^6 + 1{,}696q_1^7 + 12{,}264q_1^8 + \cdots)]. \end{aligned} \tag{5}$$

Introducing the value of z_0 from (4) into (2) we find for the maximum force

$$f_m = \frac{96\pi^2}{\sqrt{5}}\,q^2(1 + 2q^2 + 64q^4 - 252q^6 + 4{,}882q^8 - 50{,}480q^{10} + 631{,}392q^{12} - \cdots). \tag{6}$$

Equation (5) is only to be used for circles relatively close together, where formulas (4) and (6) do not give a sufficiently convergent result.

Since in most cases only a few terms need to be calculated, these formulas

are by no means as elaborate as they may appear. The great difficulty under which they labor lies in the fact, that the quantities q and q_1 are functions of z and are only approximately known beforehand. The calculation of the maximum force by these formulas can therefore be carried through only by successive approximations. The work can however be very much shortened if the value of z_0 can previously be found *approximately* by some other means.

In the case of an actual current balance, this condition will be realized experimentally. If the ratio of the radii is not greater than one half, the approximate relation given by Rayleigh,

$$z_0 = \frac{A}{2}\left(1 - 0.9\,\frac{a^2}{A^2}\right),$$

is of service. For the general case, the author has found the following empirical relation of value.

If through any element of the larger circle a plane be passed, including the common axis of the circles, then lines drawn from the element to the ends of that diameter of the smaller circle, which is determined by its intersection with the plane subtend an angle, which when multiplied by the ratio A/a of the radii, gives a value of about 46°, in no case being less than 45° nor greater than 46°.5. The author has prepared a table giving the value of this angle, for use in interpolating an approximate value of z_0 when no better method may be employed.

Having obtained an approximate value of z_0, the calculation of a precise value may be carried out as follows. Applying formula (4) or (5), a second approximation for z_0 is derived. Denoting by $\Delta z/z$ the difference between the first and second approximations, two simple differential formulas give the value of $\Delta q/q$ corresponding, and the value of $\Delta z/z$ for a third approximation. By repeating this process, a very precise value of z_0 is quickly obtained, and this may be checked and any slight necessary correction found by a second calculation by formula (4) or (5).

DIRECT MEASUREMENT OF THE VELOCITY OF KATHODE RAYS AND THE VARIATION OF MASS WITH VELOCITY.[1]

BY E. LEON CHAFFEE.

THE following is an outline of an investigation which is in progress, the object of which is to determine, by the direct measurement of the velocity of rapidly moving kathode particles together with the measurement of the deflection in a known magnetic field, the variation of the mass of the particles as a function of their velocity, and to add experimental evidence on the side of the Lorentz-Einstein theory or of the Abraham theory.

The radical difference between this investigation and other similar ones is in the method of measuring the velocity of the kathode rays, which method is free from assumptions and serious experimental errors.

[1] Abstract of a paper presented at the Cambridge meeting of the Physical Society, April 27, 1912.

Kathode rays are emitted in a high vacuum and are given a high velocity by differences of potential obtained from a large secondary battery. Potentials up to 40,000 volts have been used, and it is hoped to go to 140,000 volts by the same means. The kathode rays, after passing through a small aperture, enter a tube about 150 cm. long and finally impinge on a fluorescent screen at the end of the tube. The tube is inclined so that its axis is coincident with the direction of the earth's magnetic field. The kathode particles are timed in traversing a certain distance in the tube by means of electrical oscillations.

A new system for producing high-frequency electrical oscillations, which was described by the writer in the November issue of 1911 of the Proceedings of the American Academy of Arts and Sciences, supplies continuous undamped oscillations of 20 meters wave-length (n = 15,000,000 per sec.) to a coil about the tube, the coil being in such a position as to produce deflections of the kathode rays in a direction transverse to the axis of the tube. The coil is capable of rotation about the axis of the tube. About 70 cm. above this deflecting coil are electrostatic deflecting plates which are connected to the terminals of the condenser of the oscillatory circuit. The combined effect of the two deflecting fields on the kathode particles is to produce, on the fluorescent screen, an ellipse, the eccentricity of which depends upon the velocity of the kathode rays in traversing the distance between the two deflecting fields, upon the ratio of the deflecting powers of the two fields, and upon the angle between the planes of deflection of the two fields. Under *one* condition only does the ellipse become a circle, and when this is so the angle between the planes of the two deflecting fields is a function of the distance between the fields, the period of the oscillatory circuit, and the velocity of the kathode particles.

The measurements consist in varying the angle between the fields until a circle, as judged by the eye, is obtained. This adjustment can be made with surprising accuracy, and, by making several settings under the same conditions, the probable deviation of the mean velocity is of the magnitude of 4. per cent.

JEFFERSON PHYSICAL LABORATORY,
CAMBRIDGE, MASS.

A METHOD OF USING THE PHOTOELECTRIC CELL IN PHOTOMETRY.[1]

BY EDWARD L. NICHOLS AND ERNEST MERRITT.

IT has been shown by Richtmyer that photoelectric cells containing sodium or potassium, made by the method first described by Elster and Geitel, give a current on illumination which is strictly proportional to the intensity of the exciting light through a very wide range, provided only that the quality of the light remains unchanged. We have recently used such a cell in determining the density distribution in the negatives obtained when photographing

[1] Abstract of a paper presented at the New York meeting of the Physical Society, March 2, 1912.

certain luminescence spectra, our purpose being to locate the crests of several faint and rather diffuse bands, and we find the method both convenient and reliable.

The photoelectric cell—a potassium cell obtained from Müller-Uri, Braunschweig—was mounted in a light-tight box, one side of which contained an adjustable slit, so placed that light entering the slit fell upon the sensitive surface of the cell. The negative was mounted immediately in front of the slit, and was carried by a micrometer screw. A mercury lamp was used as a source of light. To obtain sufficient detail the slit was made somewhat less than 0.1 mm. wide.

Under these circumstances the photoelectric current was too small to be measured by a galvanometer, and it was therefore necessary to use an electrometer. In order that the current might be indicated by the deflection of the electrometer rather than by the rate of change of the deflection the cell was connected as shown in the figure. The potassium terminal of the cell K was connected to one pair of quadrants of the Dolezalek electrometer and also, through a resistance R, to earth, the other terminal of the cell being connected to the positive side of a 110-volt circuit. The resistance R consisted of a capillary tube containing absolute alcohol, and could be adjusted by varying the depth of immersion of the wire leading to earth. Since a small current passed through the cell even without illumination, it was found convenient to connect the other pair of quadrants to P, and by adjustment of the resistances S and T to bring the two pairs of quadrants to the same potential when the cell was in the dark. The deflection of the electrometer upon illuminating the cell was then a measure of the intensity of the light entering the slit.

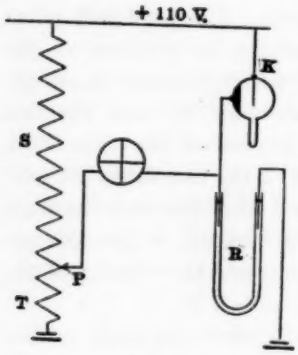

Fig. 1.

Readings could be taken with great rapidity. In one instance, for example, over four hundred readings were taken, covering the range from 4,338 A.U. to 5,790 A.U., in less than an hour. Since the quadrants of the electrometer are permanently connected to earth through the resistances R and T the instrument is almost entirely free from electrostatic disturbances. The fact that the quantity sought is measured by a deflection, rather than by the rate of change of a deflection, leads to a considerable increase in the convenience with which observations may be made; while the sensibility of the method may be made many times greater than that used in the work here described.

The Diurnal Range of Temperature and Other Meteorological Elements at Different Levels above Mount Weather.[1]

By Wm. R. Blair.

THE data for this study are being obtained by means of kites and captive balloons. A time is selected when the weather will probably be clear and the winds good for the following 30 to 36 hours, and a series of ascensions to a height of 3 kilometers or a little more above sea level is made. The ascensions of this series are in as close succession as it is possible to make them. The meteorograph carried by the head kite records air pressure, temperature, and humidity and wind velocity. Wind direction is determined to the nearest of 16 points by observation of the direction in which the kites are flying. The difference of electrical potential between the kite and the earth's surface is also observed. Three series have been made, two in the late summer, 1911, and one in the late winter, 1912.

These data have all been reduced and tabulated and charted so as to show the variation in each element recorded at levels 0.5 kilometer apart up to 3 kilometers in the summer series and up to 2.5 kilometers in the winter series. The departures of the hourly temperatures from the mean for the day are less at a level between 1.5 and 2 kilometers than either below or above it. Below this transition level the greatest positive and negative departures from the mean temperature for the day decrease and incline slightly forward with altitude. Above it the positions of these departures are very nearly transposed, the negative one occurring at about 1 to 2 P.M. and the positive one at 2 to 5 A.M. The observations of air pressure are used in computing the altitudes. Aside from this and the electrical potential of the atmosphere, the other elements observed have a less characteristic diurnal range than the temperature. The atmospheric potential is decidedly lower at all levels during the day than during the night hours. The minimum follows the time of maximum insolation.

Mount Weather Observatory,
Bluemont, Va.,
April 12, 1912.

On the Effect of Light on a Helix of Rays from the Wehnelt Cathode (Experimental).[1]

By Chas. T. Knipp.

THE paper is an account of an experimental attempt to test J. J. Thomson's corpuscular or pulse theory of light. His helical cathode beam indicator was employed. The principle of this method is that such a beam forms a sensitive indicator when struck, near its source, by radiation containing either positively or negatively (or both) charged carriers. The effect on the beam

[1] Abstract of a paper presented at the Cambridge meeting of the Physical Society, April 27, 1912.

would be to make it fuzzy, or if allowed to fall on a photographic plate the image should show blurred. A helical beam 47 cm. long, of pitch about 1 cm., and 4 to 8 mm. in diameter, was obtained by using the form of cathode and general mounting described in the PHYSICAL REVIEW, Vol. XXXIV., p. 58. Photographs were taken, first, of the beam alone, and second, of the beam when the end near the source, for a space of 1.5 cm., was illuminated by the light from a lantern. This was followed by another exposure without the lantern. Three dozen plates were thus exposed, some having six exposures on them—three without and three with the lantern. The conditions under which the different plates were exposed varied very widely, though for a given plate the conditions were practically constant, the six exposures occupying less than two minutes. The time of a single exposure was about one tenth of a second. The plates almost without an exception show an *effect*. On some it is more marked than on others. The effect thus far observed is *to reduce the size of the image* on the photographic plate. The circular image on a number of plates shows blurred towards the center, but not outwards. The effect is more marked when the image is not too clearly cut, *i. e.*, when the vacuum is not too high. Again, it also seems more marked when the tube is operated on low voltages. The incident light in general fell on but one turn of the helical beam. By adjustment of the field the helix could be wound up so as to present a convex or a concave arc towards the incident light. This, however, does not seem to alter the effect. For the want of data taken under sufficiently varying conditions it is impossible at this time to explain the phenomenon, and to state whether it agrees with Thomson's theory of light.

LABORATORY OF PHYSICS,
UNIVERSITY OF ILLINOIS,
April 12, 1912.

A THEORETICAL CORRECTION TO THE DROP METHOD OF DETERMINING "*e*."[1]

BY ARTHUR C. LUNN.

THE absolute determination of the elementary charge by the use of a drop of liquid as carrier of the ions depends on the measurement of the steady velocity of the drop through the surrounding medium under gravity, with and without the presence of an electrostatic field. The computation assumes that the factor of mobility of the drop is the same in both cases. If however the liquid has a dielectric constant different from that of the medium the Maxwell surface stresses produced by the field tend to distort a spherical drop into a somewhat ellipsoidal form up to the point where they are equilibrated by the normal component of surface tension forces which corresponds to the variation of curvature of the surface. In this paper a sufficiently

[1] Abstract of a paper presented at the Cambridge meeting of the Physical Society, April 27, 1912.

approximate formula is obtained for the amount of this ellipticity. The corresponding correction to Stokes' law for a sphere is shown to be inappreciable in the most extreme cases under the actual conditions of Millikan's measurements, as already inferred by him from the experimental data.

Magnetic Induction in a Group of Oblate Spheroids of Iron.[1]

By S. R. Williams.

THE magnetic induction in a group of twenty-seven oblate spheroids of soft iron was studied when the equatorial planes of the spheroids were oriented in different azimuths with respect to the imposed magnetic field. The twenty-seven spheroids were mounted so that they formed a cube with nine spheroids on a side. This group was tested by the ballistic method just as any specimen of iron would be. It was found that the induction was larger the more nearly the spheroids were turned with the equatorial planes parallel to the magnetic field. In other words if the spheroids were oriented so that their equatorial planes were all parallel to each other the induction varied in different directions in the cube.

This behavior of the group of spheroids is very much like the behavior of iron electrolytically deposited in a magnetic field, which shows different magnetic properties parallel to the field in which it was deposited from what it does at right angles to this direction.[2] Again it is similar to the behavior of pyrrhotine which Weiss[3] investigated and found it possessed directions in which greater magnetic intensities occurred than in others.

In conjunction with the theory of magnetism proposed in the paper, "A Model of the Elementary Magnet,"[4] this deportment of the oblate spheroids readily explains the cause of the Villari reversal effect, the behavior of certain crystals in a magnetic field and particularly the reason why the knee of the induction curve of hardened steel is flatter than that of soft iron.[5]

Physical Laboratory, Oberlin College,
Oberlin, Ohio,
March 21, 1912.

Absolute Formulæ for the Attraction of Two Coaxial Solenoids.[1]

By G. R. Olshausen.

THE mutual inductance of two coaxial solenoids is given by the expression

$$M = 4\pi nn'[I_1 - I_2 - I_3 + I_4],$$

[1] Abstract of a paper presented at the Cambridge meeting of the Physical Society, April 27, 1912.

[2] Maurain, Sci. Abstracts, No. 2235, 1900.

[3] Weiss, Jour. d. Phys., Vol. IV., pp. 469, 829.

[4] Williams, Phys. Rev., Vol. 34, Jan., 1912.

[5] Hadley, Elec. and Mag., p. 390, 1908.

where n and n' are the respective numbers of turns per unit length of the two coils and the quantities in brackets are integrals of the form

$$I = a_1^2 a^2 \int_0^\pi \frac{\sin^2\psi d\psi}{a_1^2 + a^2 - 2a_1 a\cos\psi} \sqrt{a_1^2 + a^2 + c^2 - 2a_1 a\cos\psi}.$$

In this expression a_1 and a are the respective radii of the coils and c has the following values:

$$\begin{aligned} c &= d + l + l_1 \quad \text{for} \quad I = I_1, \\ c &= d + l_1 - l \quad \text{for} \quad I = I_2, \\ c &= d + l - l_1 \quad \text{for} \quad I = I_3, \\ c &= d - l - l_1 \quad \text{for} \quad I = I_4, \end{aligned}$$

where d is the distance between centers of the coils and $2l_1$ and $2l$ are their respective lengths.

The attraction of the two solenoids, when a unit current flows through each, is then

$$-\frac{\partial M}{\partial d} = -4\pi nn'\left[\frac{\partial I_1}{\partial c_1} - \frac{\partial I_2}{\partial c_2} - \frac{\partial I_3}{\partial c_3} + \frac{\partial I_4}{\partial c_4}\right].$$

The differential coefficients are found by differentiating the above value of I under the integral sign with respect to c. We obtain then

$$\frac{dI}{dc} = \frac{c(m\beta)^{\frac{1}{2}}}{2}\int_{\omega_3}^{\omega_2} \frac{(pu - e_2)(pu - e_3)}{pu - pw}\, du.$$

The constants entering into this and the following expressions and the variable u have the same significance as in my paper on "Absolute Formulæ for the Mutual Inductance of Two Coaxial Solenoids," PHYS. REV., 31, pp. 617–636, December, 1910.

On integrating, we obtain the following four equivalent values of dI/dc.

$$(a)\quad \frac{dI}{dc} = \frac{c(m\beta)^{\frac{1}{2}}}{2}\left[\frac{4(a_1^2 + a^2) + c^2}{3m\beta}\omega_1 - \eta_1 + \frac{i(a_1^2 - a^2)}{|c|(m\beta)^{\frac{1}{2}}}\left\{\eta_1 w_1 i - \omega_1 \frac{\sigma_1'}{\sigma_1}(w_1 i)\right\}\right],$$

$$(b)\quad \frac{dI}{dc} = \frac{c(m\beta)^{\frac{1}{2}}}{2}\left[\frac{a_1^2 + a^2 + c^2 + 6a_1 a}{3m\beta}\omega_1 - \eta_1 + \frac{i(a_1^2 - a^2)}{|c|(m\beta)^{\frac{1}{2}}}\left\{\eta_1 w_1 i - \omega_1 \frac{\sigma_2'}{\sigma_2}(w_1 i)\right\}\right],$$

where $|c|$ indicates that the absolute value of c is to be used in all cases.

Expressed in terms of Legendre's integrals these formulæ become

$$(c)\quad \frac{dI}{dc} = \frac{c}{2}\left[\frac{2(a_1^2 + a^2) + c^2}{\sqrt{(a_1 + a)^2 + c^2}}F(k) - \sqrt{(a_1 + a)^2 + c^2}\,E(k) + \frac{a_1^2 - a^2}{|c|}\left\{F(k)\,[F(\varphi,\ k') - E(\varphi,\ k')] - E(k)\,F(\varphi,\ k')\right\}\right]$$

and

$$(d)\quad \frac{dI}{dc} = \frac{c}{2}\left[\sqrt{(a_1 + a)^2 + c^2}\,\{F(k) - E(k)\} - \frac{(a_1^2 - a^2)}{|c|}\left\{F(k)[F(\varphi,\ k') - E(\varphi,\ k')] - E(k)\,F(\varphi,\ k') + \frac{\pi}{2}\right\}\right].$$

In the first of these two formulæ

$$\sin^2\varphi = \frac{c^2}{(a_1 - a)^2 + c^2},$$

in the second

$$\sin^2\varphi = \frac{(a_1^2 - a^2)^2 + c^2(a_1 - a)^2}{(a_1^2 - a^2)^2 + c^2(a_1 + a)^2},$$

and in both of them

$$k^2 = \frac{4a_1 a}{(a_1 + a)^2 + c^2} \quad \text{and} \quad k'^2 = \frac{(a_1 - a)^2 + c^2}{(a_1 + a)^2 + c^2}.$$

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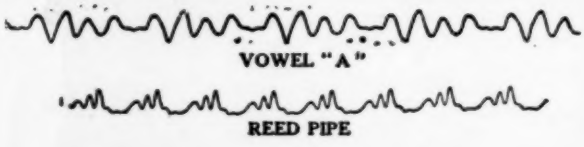

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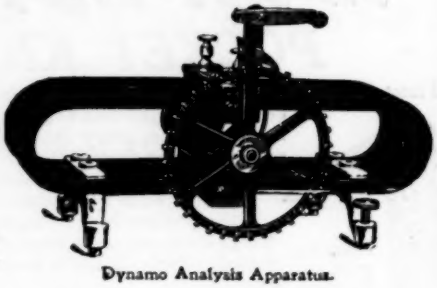

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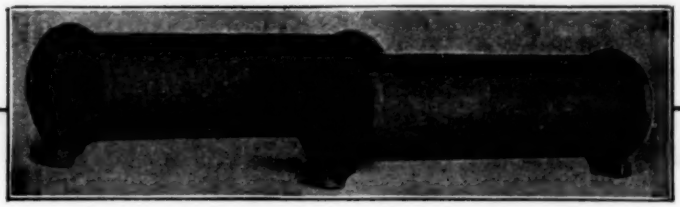

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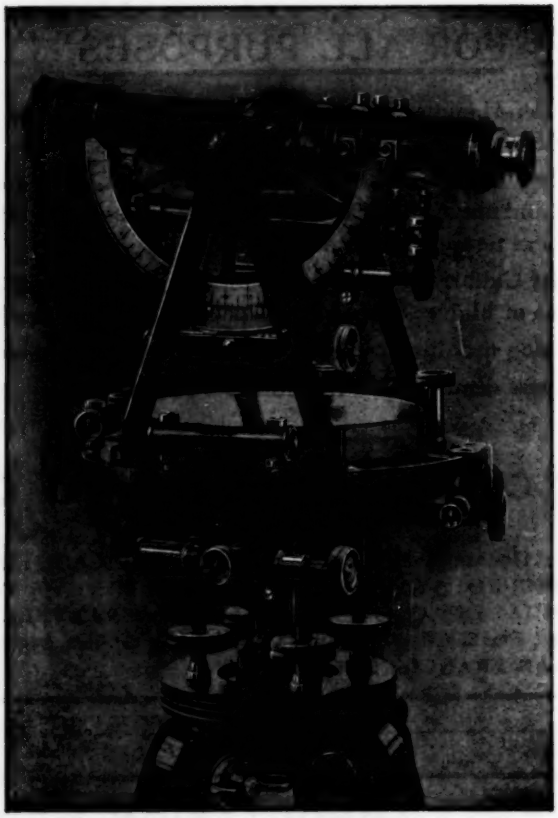

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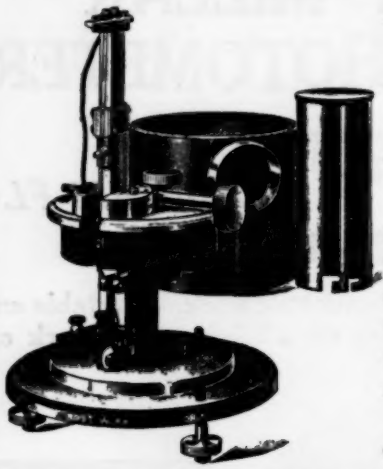

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